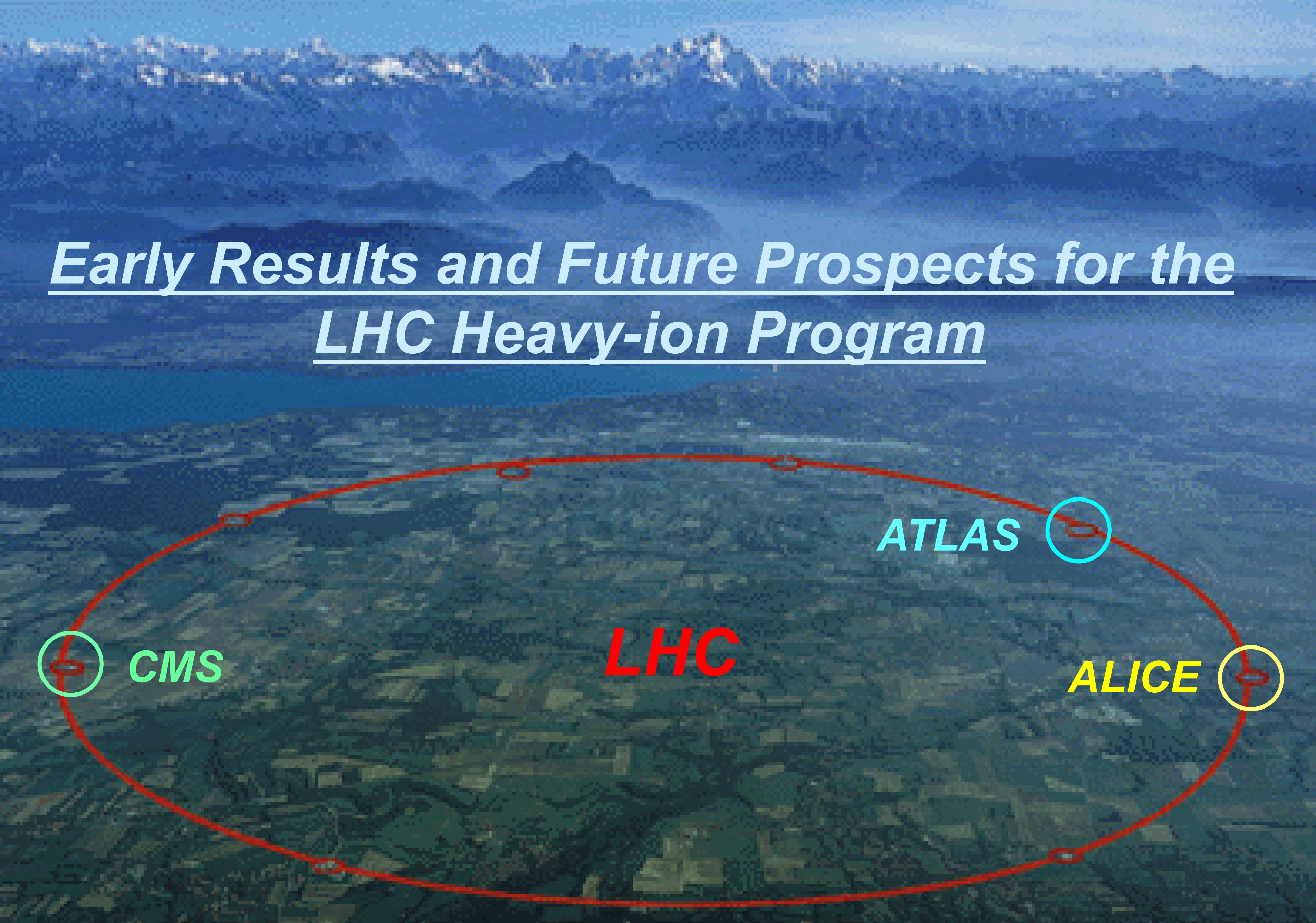
Early Results and Future Prospects for the LHC Heavy-ion Program

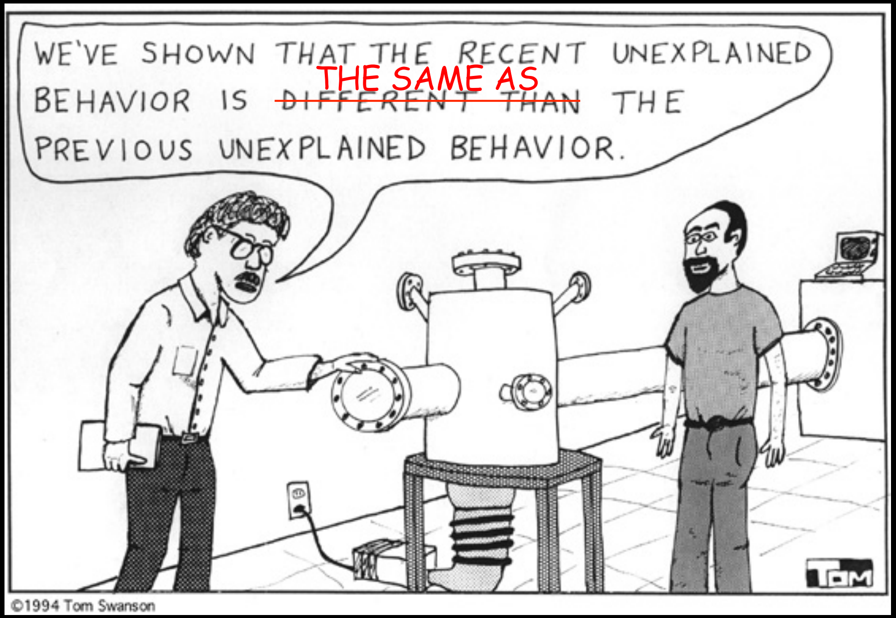


Standard Model Theorists!

Anxiety….???

The LHC Physics Program

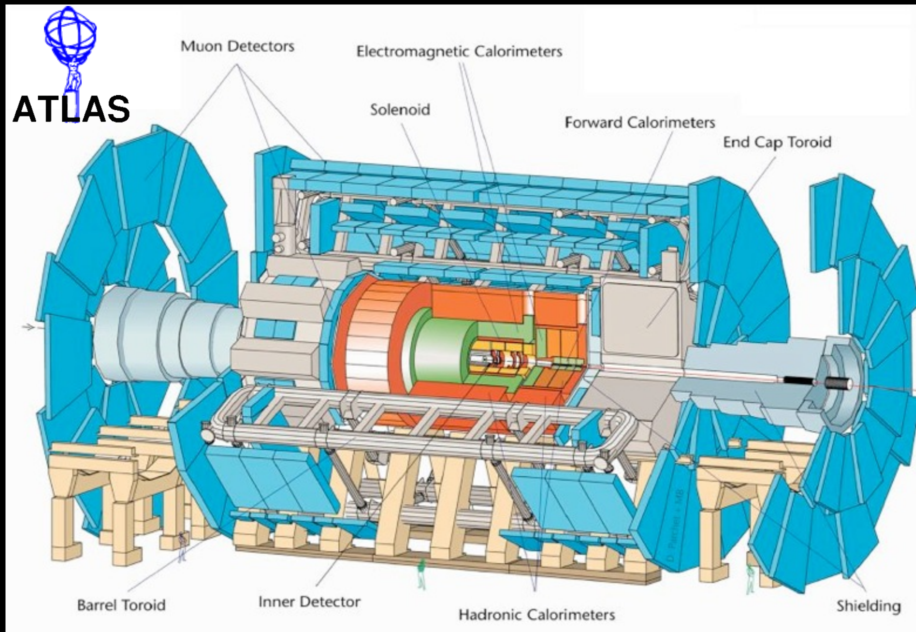
WORSE YET!



Heavy Ion Expectations vary….. vs RHIC???

The Large Hadron Collider

LHC Heavy Ion Program

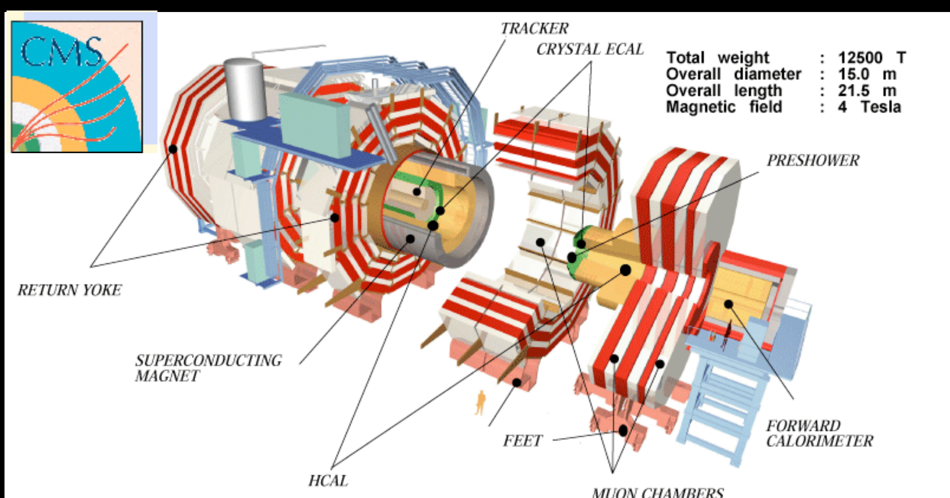


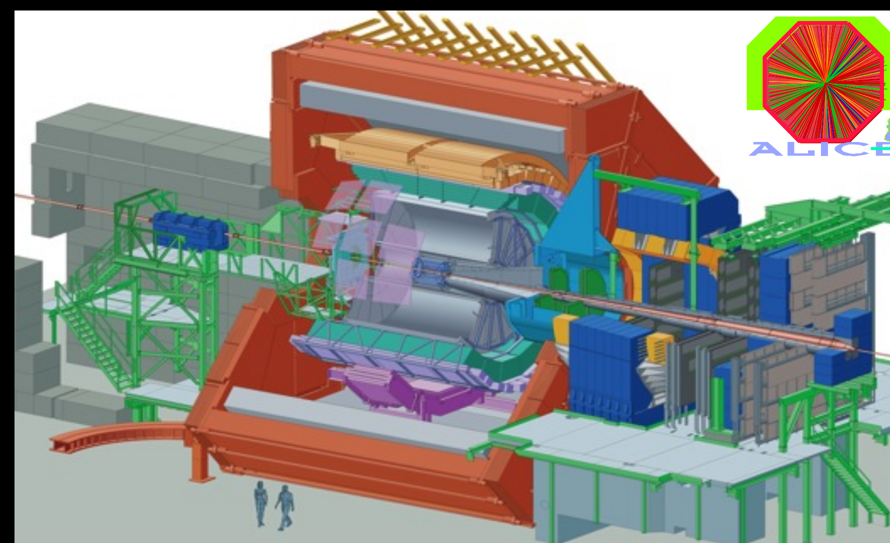
LHC Heavy Ion Data-taking

Design: Pb + Pb at $\sqrt{s_{NN}}$ = 5.5 TeV
(1 month per year)

Nov. 2010: Pb + Pb at $\sqrt{s_{NN}}$ = 2.76 TeV

- LHC Collider Detectors
  - ATLAS
  - CMS
  - ALICE

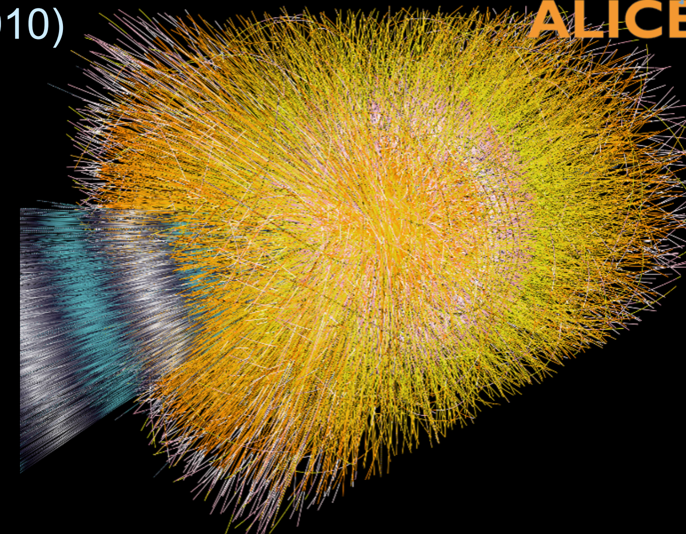




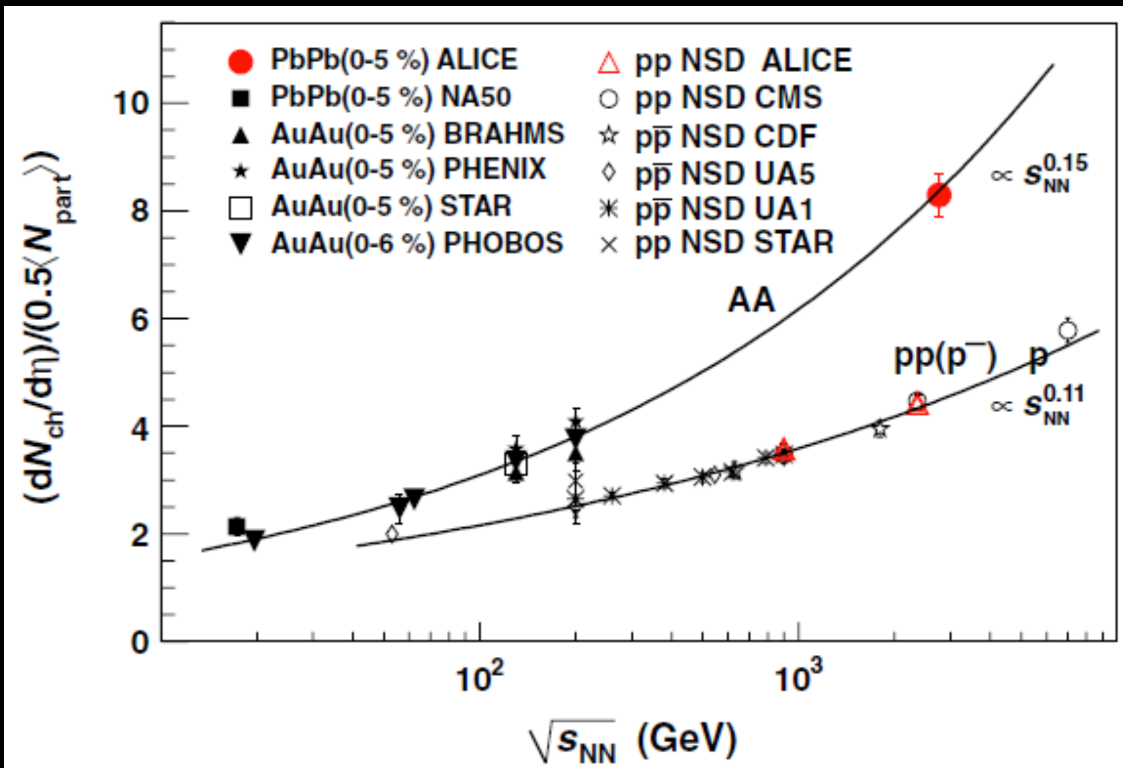
Global Observables from Heavy Ions at LHC

Charged Particle Multiplicity

ALICE, Phys. Rev. Lett. 105, 252301 (2010)



$\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb central (0-5%)



At mid-rapidity in central collision

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV:

→ 1.9 x pp at $\sqrt{s_{NN}}$ = 2.36 TeV

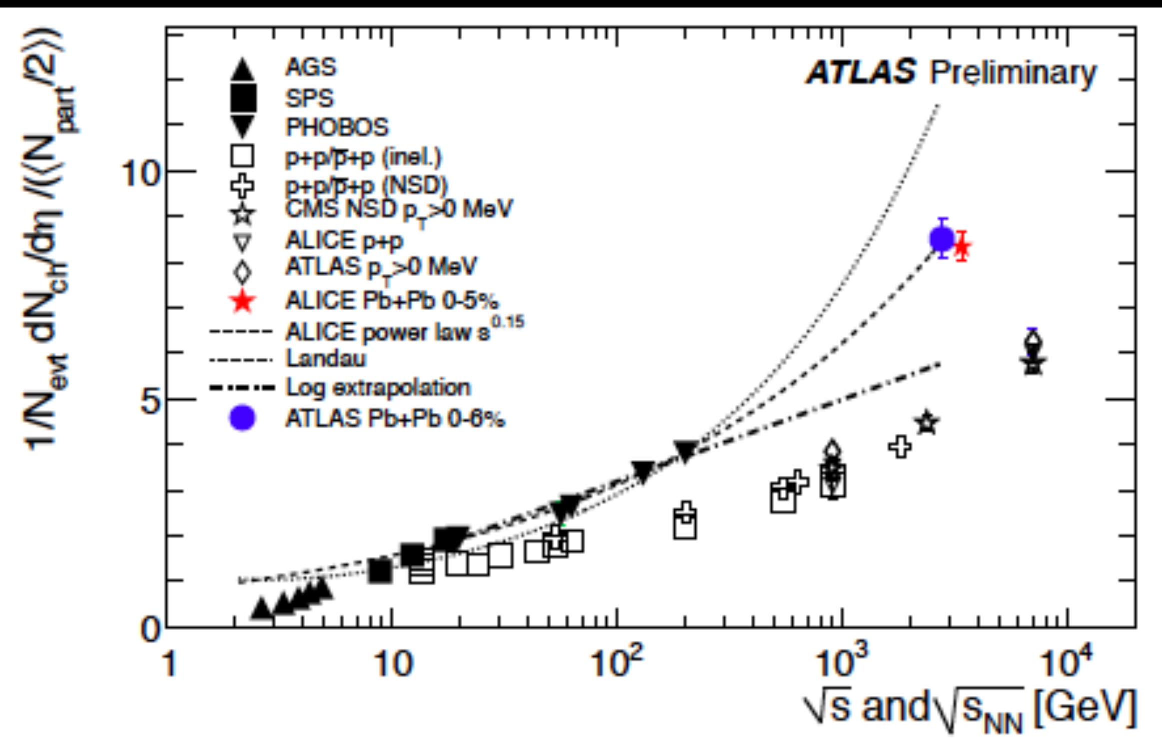
→ nuclear amplification!

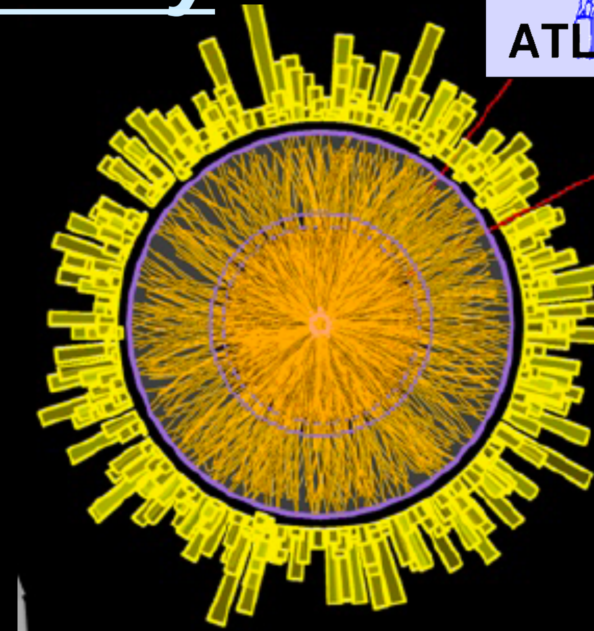
→ 2.2 x AuAu at $\sqrt{s_{NN}}$ = 200 GeV

Charged Particle Multiplicity

ATLAS, P. Steinberg QM 2011

$\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb central (0-5%)





At mid-rapidity in central collision

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV:

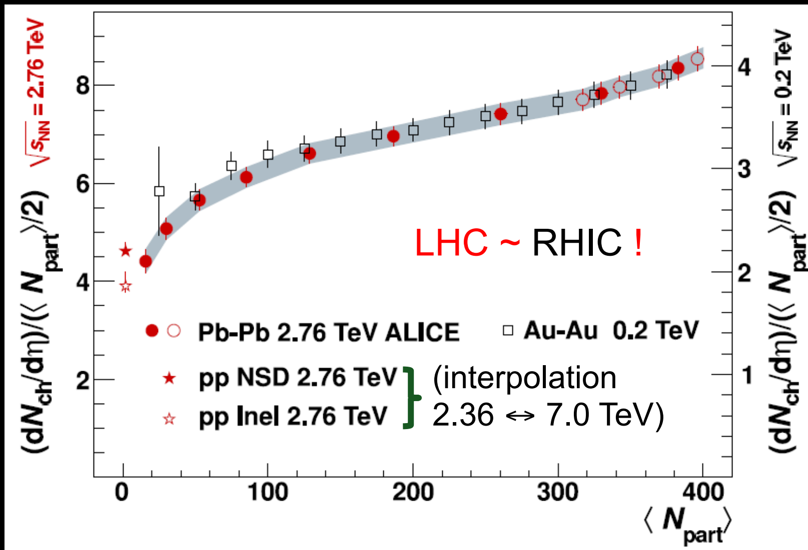
→ 1.9 x pp at $\sqrt{s_{NN}}$ = 2.36 TeV

→ nuclear amplification!

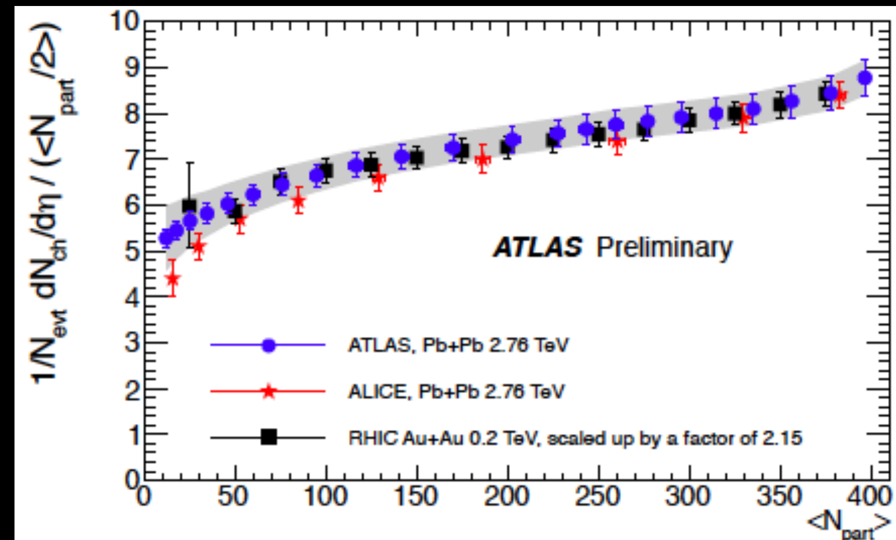
→ 2.2 x AuAu at $\sqrt{s_{NN}}$ = 200 GeV

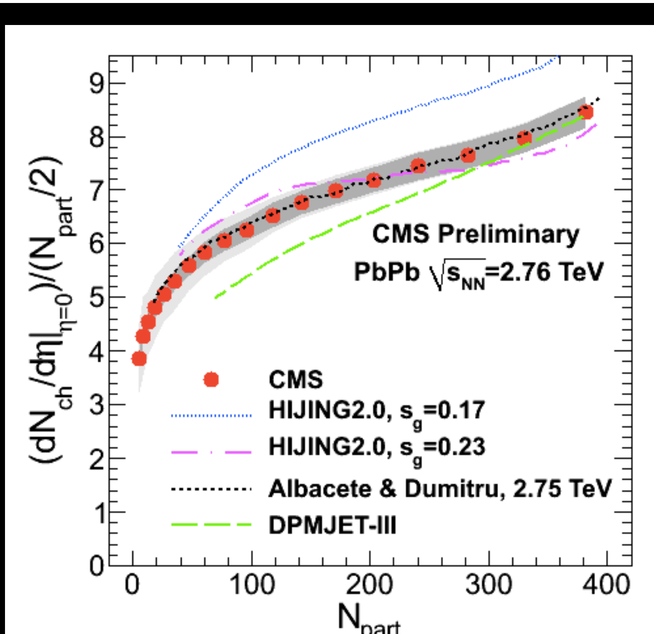
$dN_{ch}/d\eta$ – Centrality & η Dependence

ALICE, Phys. Rev. Lett. 106, 032301 (2011)

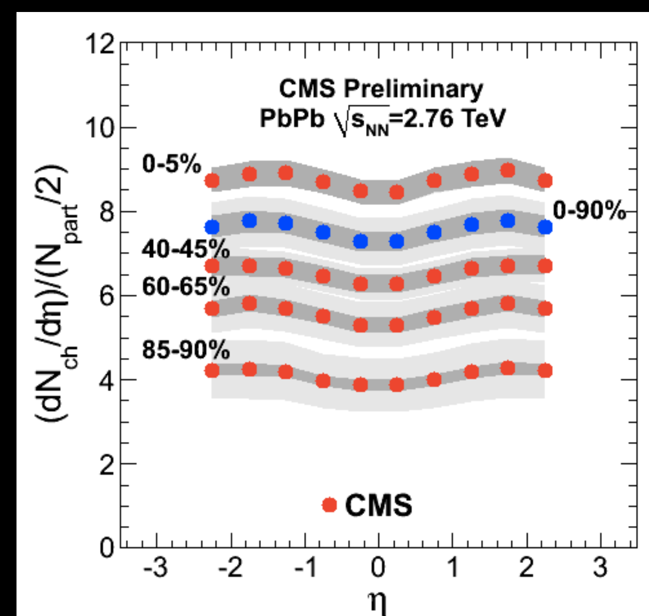


ATLAS, P. Steinberg QM2011





CMS, B. Wyslouch QM2011



$dN_{ch}/d\eta$ – Centrality Dependence vs Theory

ALICE, Phys. Rev. Lett. 106, 032301 (2011)
ALICE, C. Loizides, QM 2011

Two-component models:

Soft processes $dN_{ch}/d\eta \sim N_{\text{scattered nucleons (participants)}} \sim N_{part}$

$\therefore$ "nuclear amplification" → independent of $\sqrt{s}$

Hard processes $dN_{ch}/d\eta \sim N_{\text{nucleon-nucleon collisions}}$

$\therefore$ increased importance with $\sqrt{s}$ & centrality

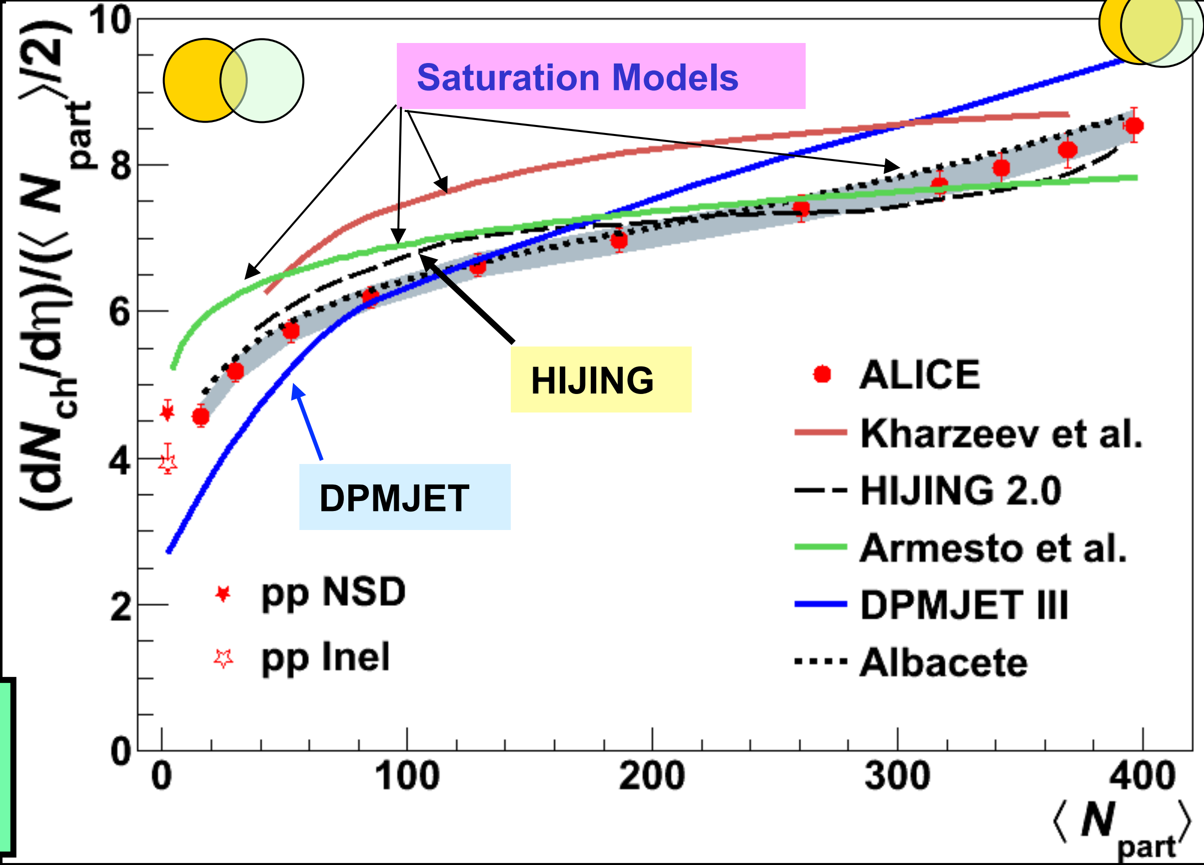
- DPMJET MC
  too strong rise with N_{part}
- HIJING MC (2.0), no quenching
  Centrality dependent – Gluon shadowing
  Tuned to 0-5% central

Saturation-type models:

Parametrization of saturation scale vs $\sqrt{s}$ & centrality (A) geometric scaling

Important constraint for models & sensitive to details of initial state, saturation, evolution….!

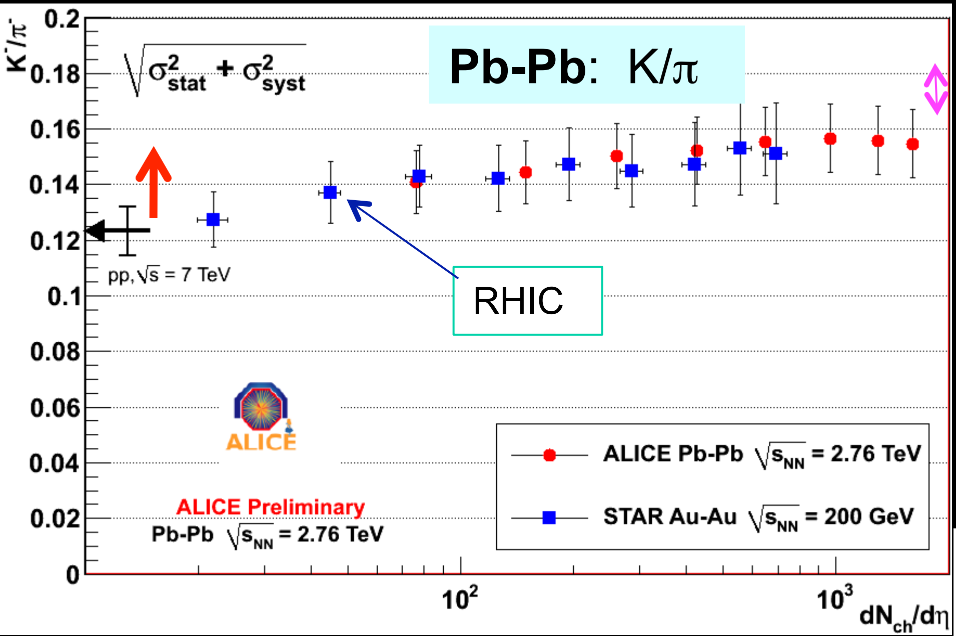
Predictions



Data favor models with moderation of particle production vs centrality (also at RHIC)!

Particle Ratios vs $dN_{ch}/d\eta$ at RHIC and LHC

ALICE, J. Schukraft QM 2011

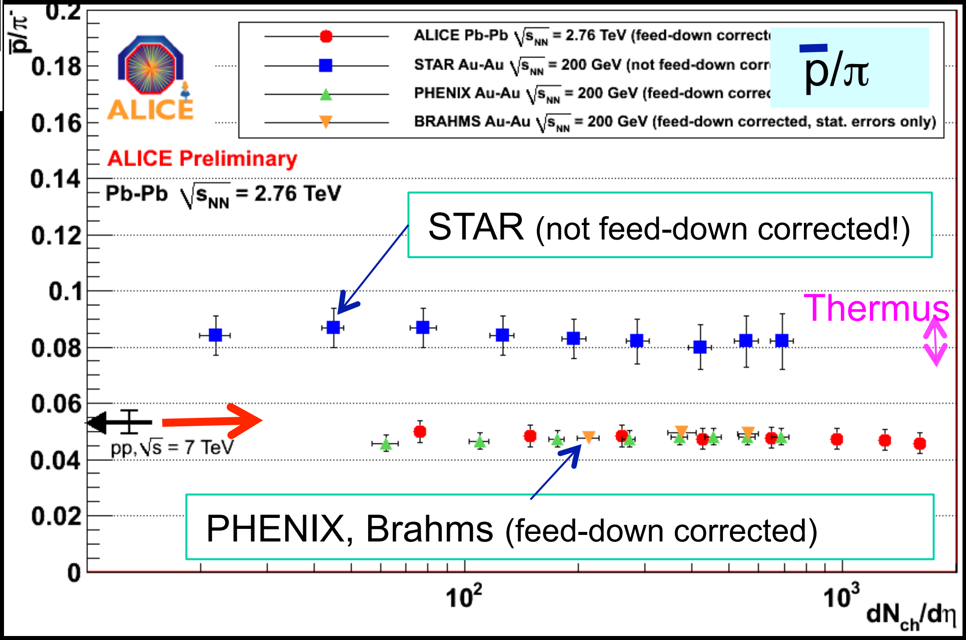


Thermus

K/π ratios similar at LHC and RHIC

Slight increase with dN/dη from pp

Lower than thermal model predictions



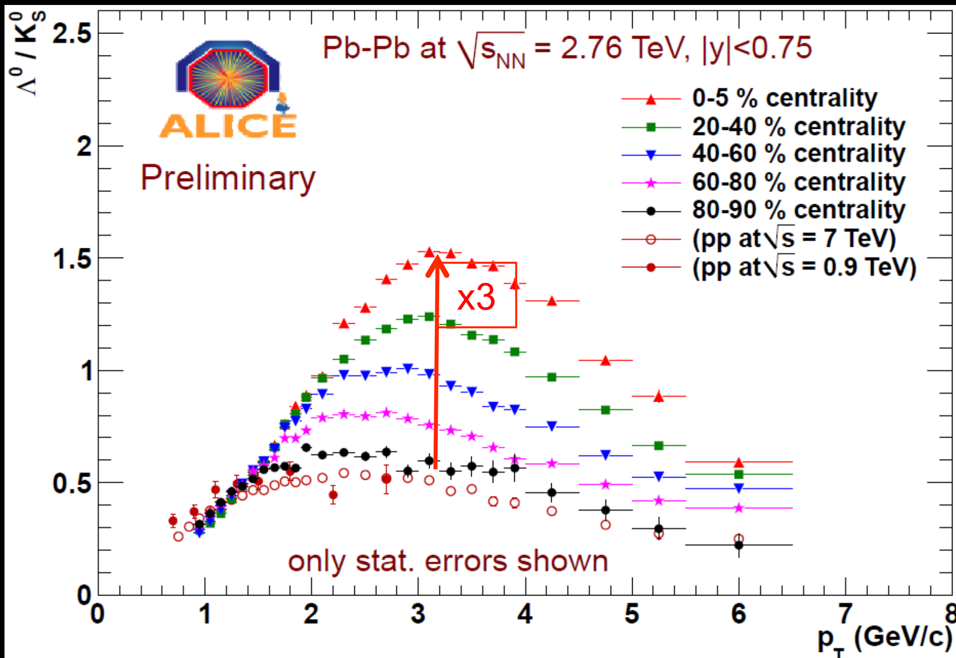
$\bar{p}/\pi$ ratios similar at LHC and RHIC

No change with dN/dη from pp value

~60% of thermal model value!

RHIC Baryon Anomaly Re-appears at LHC!

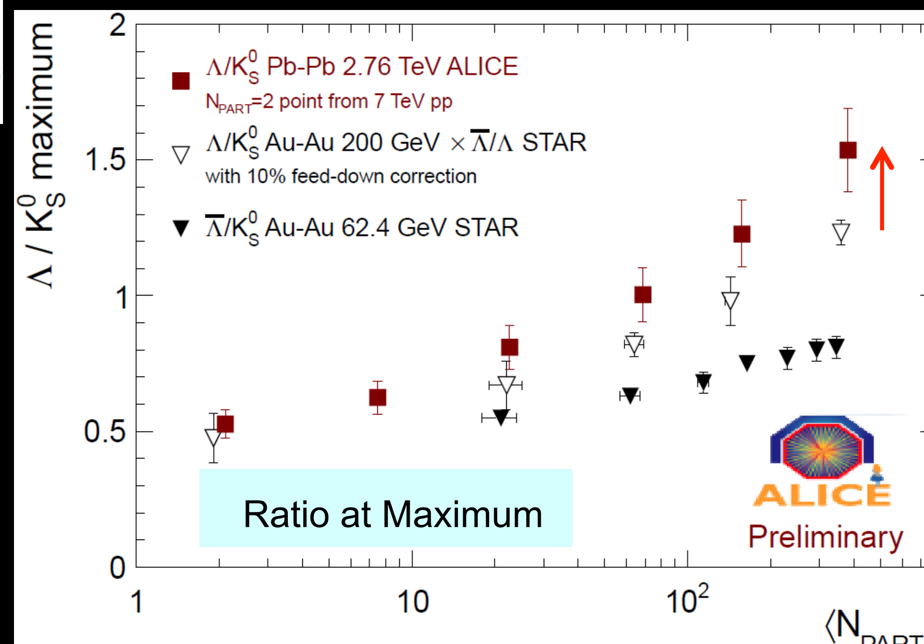
ALICE, J. Schukraft QM 2011



Enhanced baryon/meson ratio ala RHIC

Increases with centrality

Peak central B/m ratio x3 pp value

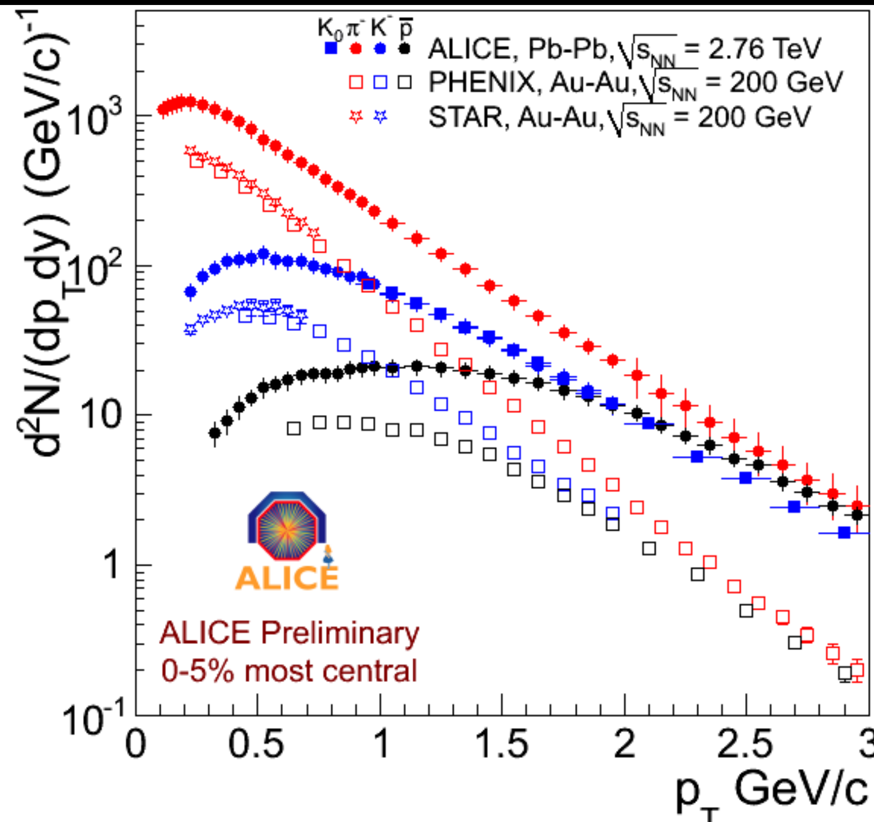


B/m ratio slightly larger at LHC than RHIC

Little change with p_T, although significant differences in spectra

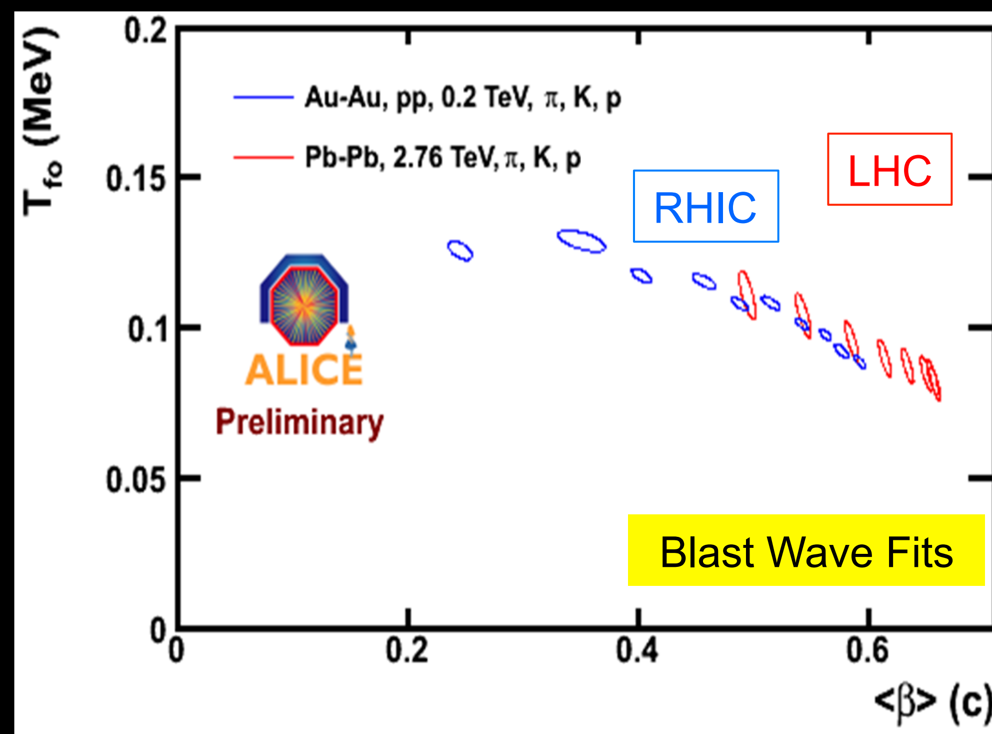
Bigger Blast in dN/dp_T for π, K, p at LHC!

ALICE, J. Schukraft QM 2011



Slope changes at LHC vs RHIC

Most dramatic for protons (in black)



Very strong radial flow,
$\beta \approx 0.66$ at LHC

Stronger than predicted by recent hydro

Central Collisions of Pb-Pb at the LHC produce

$dn_{ch}/d\eta$ per N_{part} pair ~ 2.2 RHIC

and an energy density ≥ 3 x RHIC!

Particle ratios (still few) same as at RHIC

Baryon Anomaly still exists (similar)

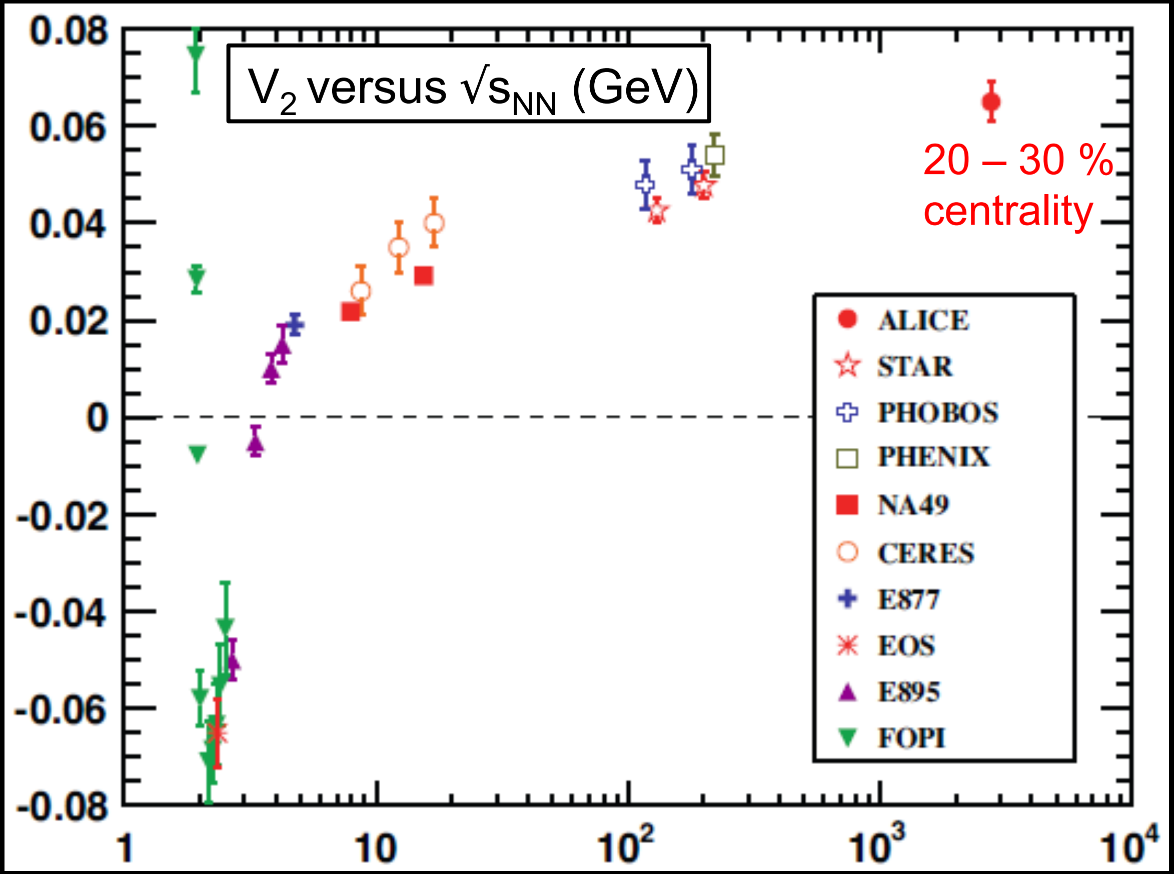
Stronger radial flow!

Elliptic Flow – Energy Dependence

ALICE, Phys. Rev. Lett .105, 252302 (2010)

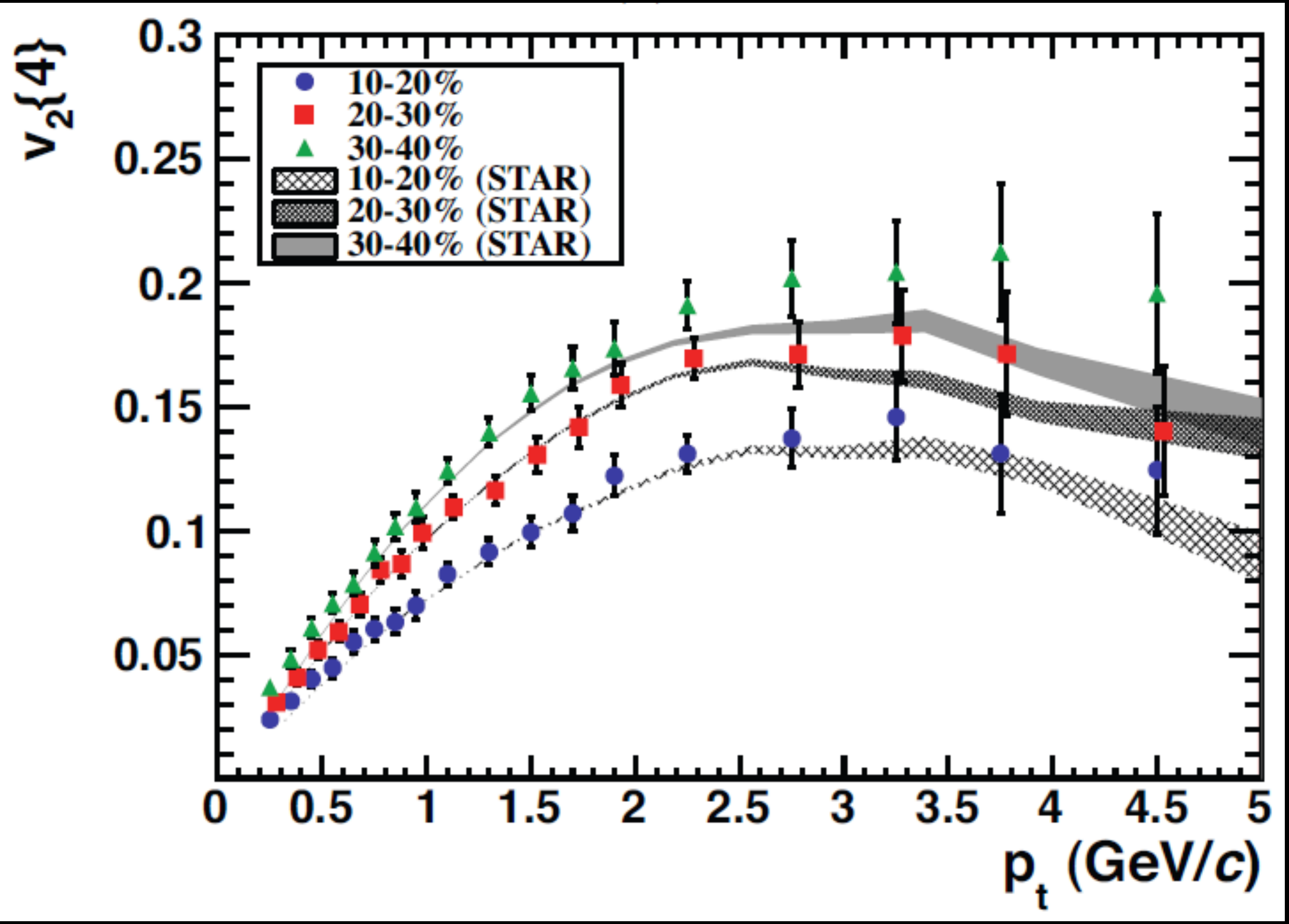
- Increase in v_2 from RHIC to LHC.

Described by hydrodynamics (various different calc's) with:
- Glauber geometry
- viscous corrections η/s still small (~0.1-0.2)
- changes expected in space-time evolution



Elliptic Flow – p_T & Centrality Dependence

ALICE, Phys. Rev. Lett .105, 252302 (2010)

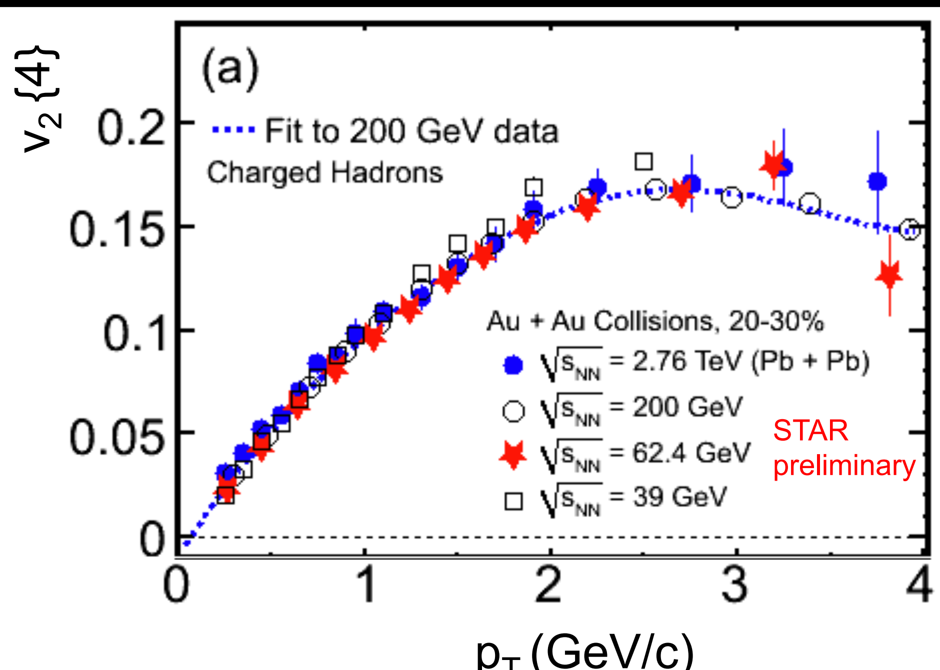


Very little change in v_2 vs p_t between 0.2 TeV (STAR) and 2.76 TeV (ALICE)

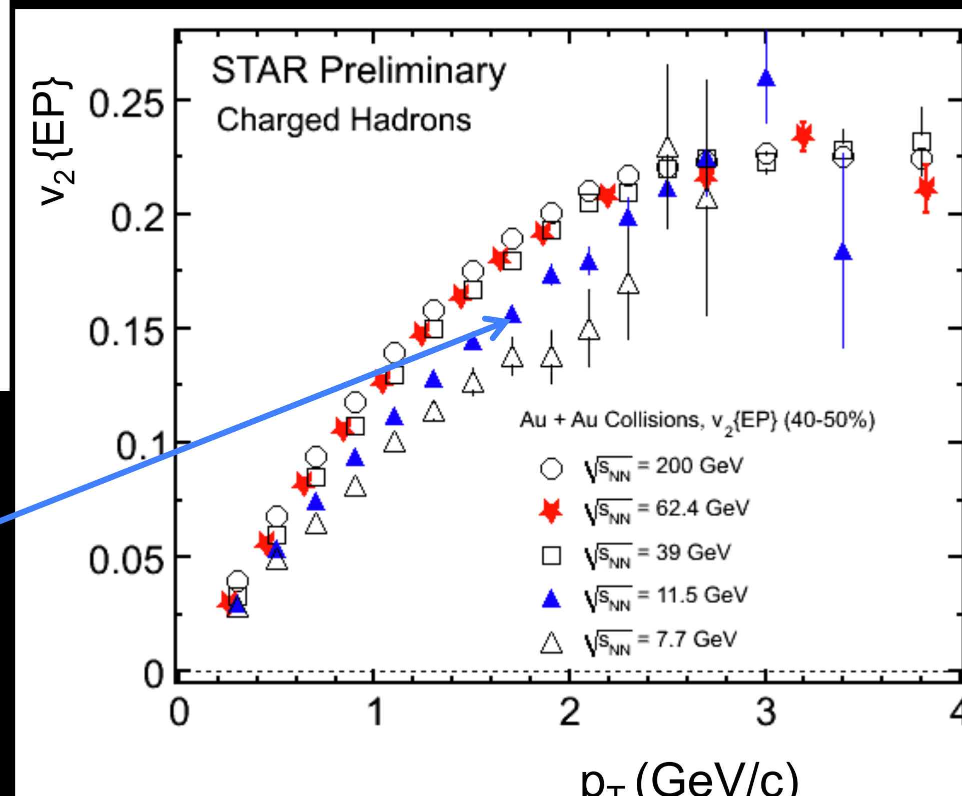
For three different centrality classes → consistent with hydro (Heinz; Eskola)!

Elliptic Flow – $\sqrt{s_{NN}}$ Dependence of $v_2(p_T)$

ALICE, Phys. Rev. Lett .105, 252302 (2010)
STAR: PRC 77 (2008) 054901; PRC 75 (2007) 054906



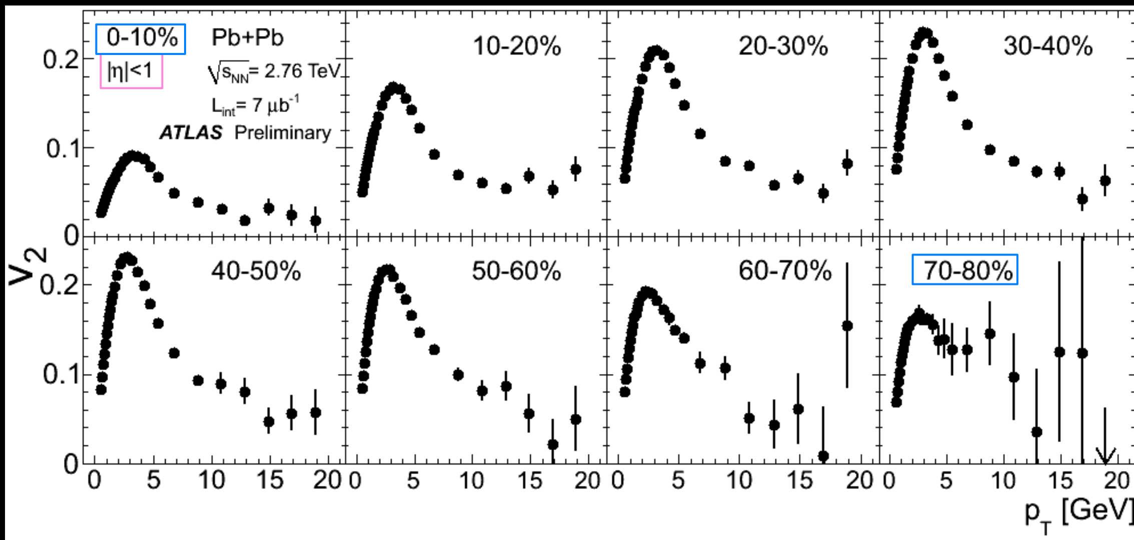
v_2 vs transverse momentum (p_T) same for 2.76 TeV down to 39 GeV!

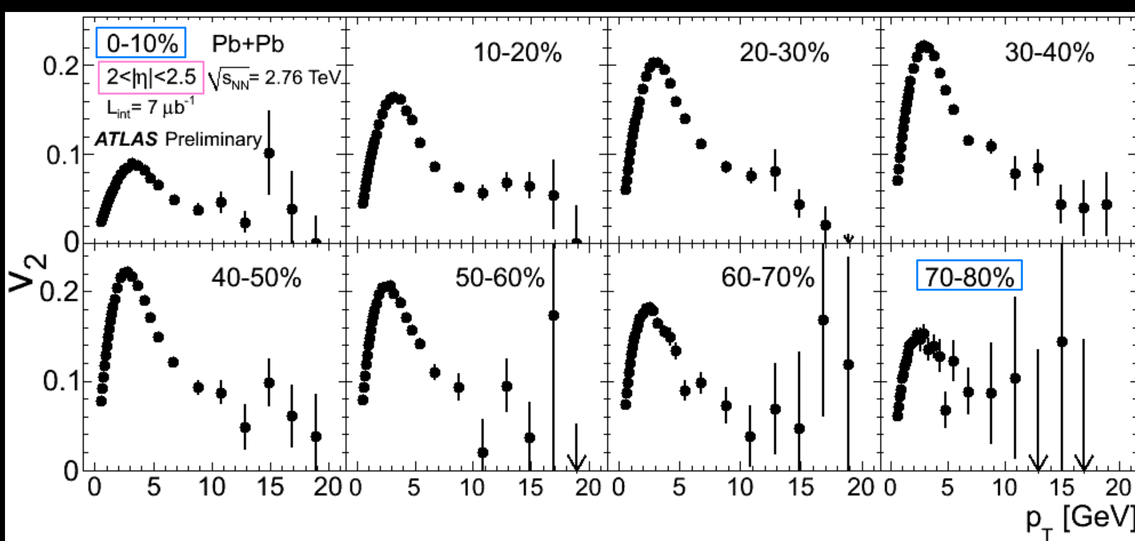


Change in v_2 vs p_T below 39 GeV (at 7.7 & 11.5 GeV)!

Elliptic Flow at Large p_T

ATLAS, J. Jia, A. Trzupek QM2011





Characteristics:

v_2 inceases (up to ~ 3 GeV/c)

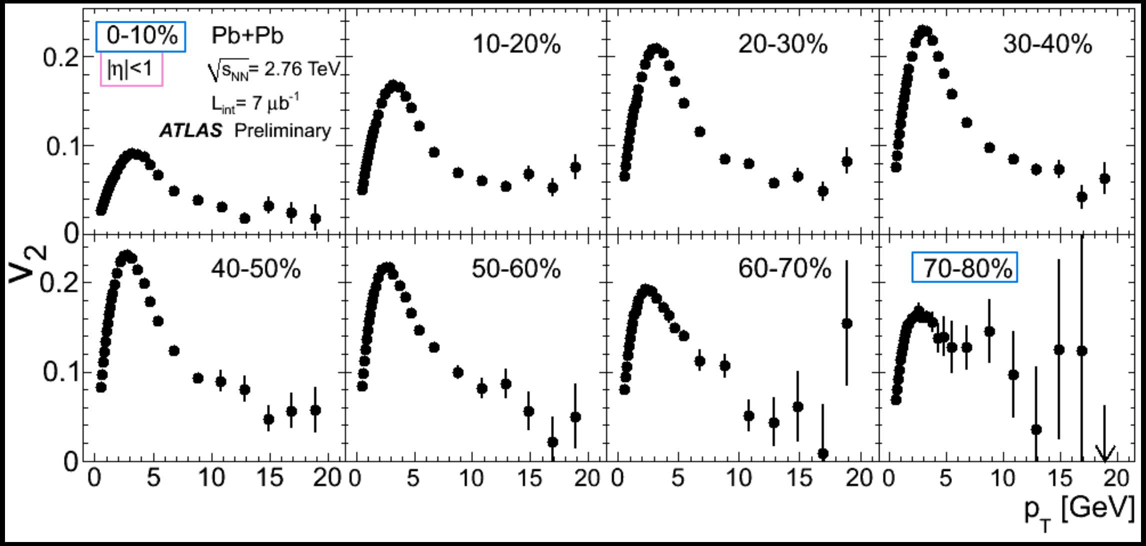
v_2 decreases (3 – 8 GeV/c)

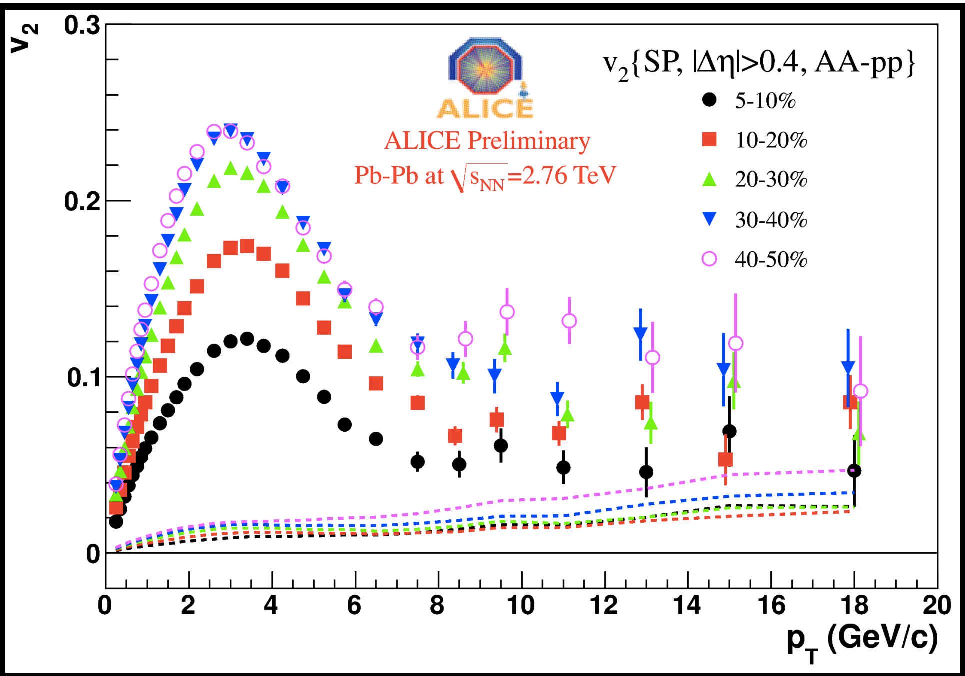
v_2 ~ flat beyond

Expected centrality dependence

Little η dependence!

Elliptic Flow at Large p_T





ALICE, A. Dobrin, QM 2011

Characteristics:

v_2 inceases (up to ~ 3 GeV/c)

v_2 decreases (3 – 8 GeV/c)

v_2 ~ flat beyond

Expected centrality dependence

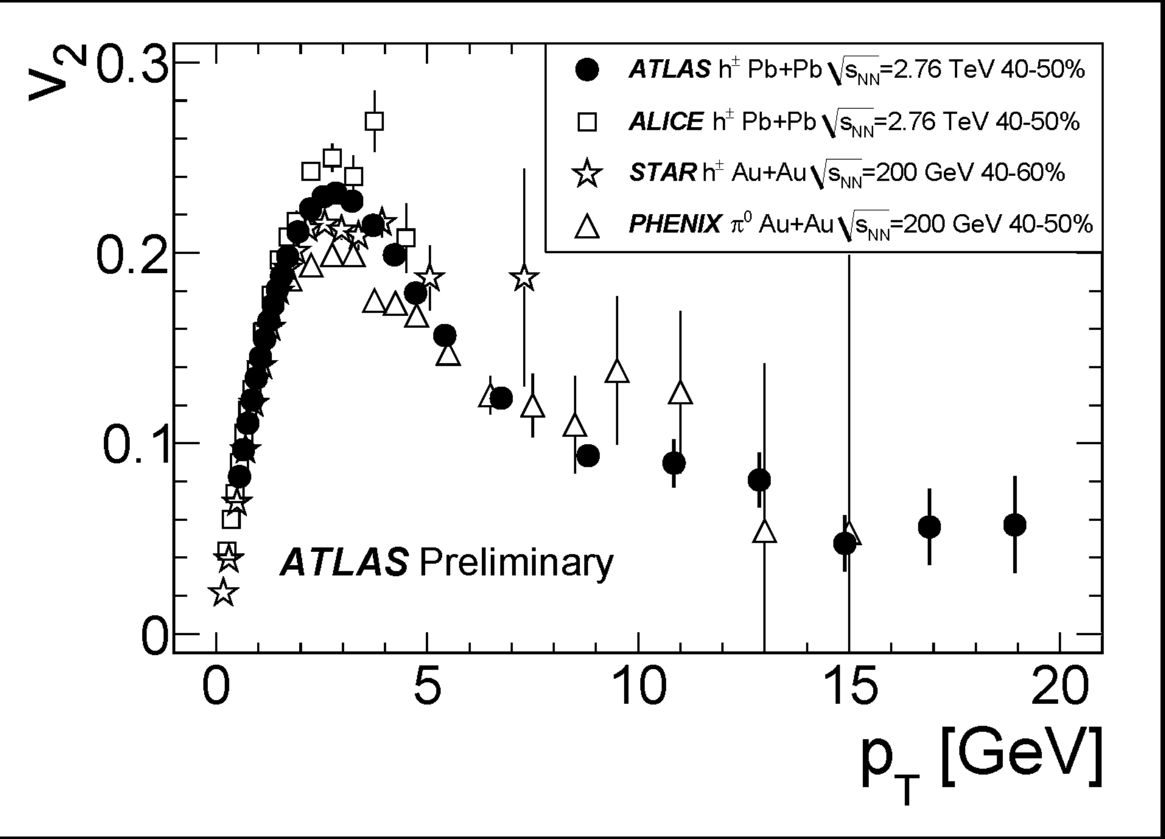
Little η dependence!

Similar in CMS and ALICE!

Elliptic Flow at Large p_T

ATLAS, J. Jia, A. Trzupek QM2011

ATLAS



Characteristics:

v_2 inceases (up to ~ 3 GeV/c)

v_2 decreases (3 – 8 GeV/c)

v_2 ~ flat beyond

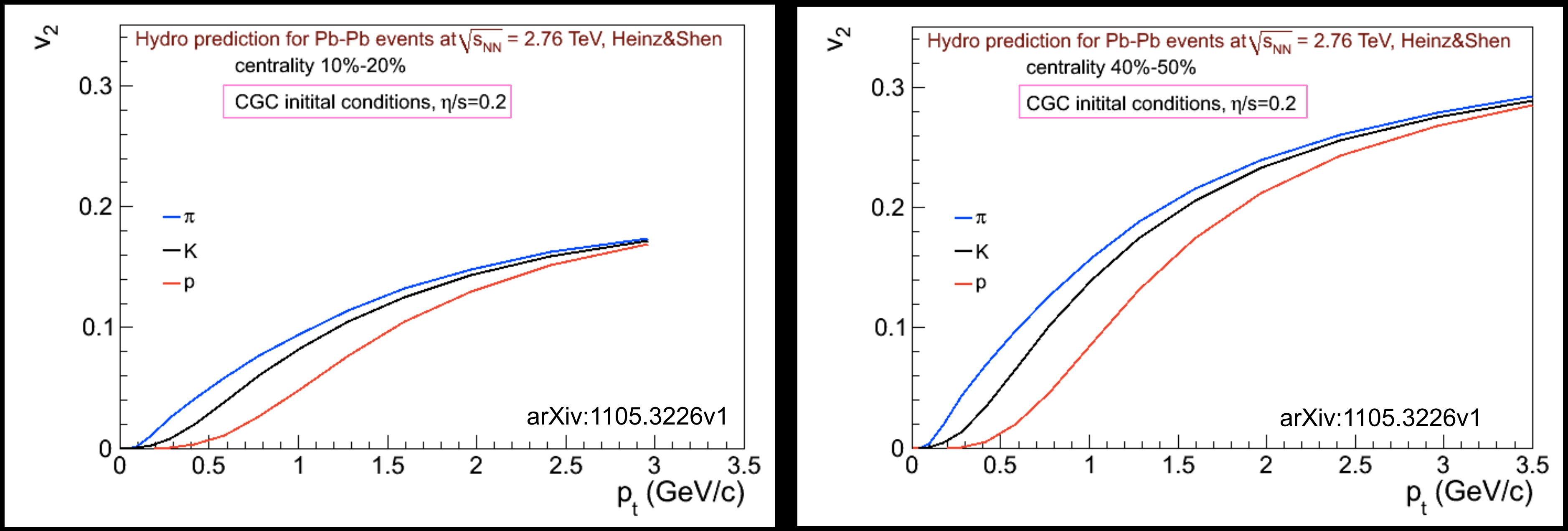
Expected centrality dependence

Little η dependence!

Little $\sqrt{s_{NN}}$ dependence!

Hydro Elliptic Flow – Identified Particles

ALICE, M. Krzewicki, R. Snellings, QM 2011

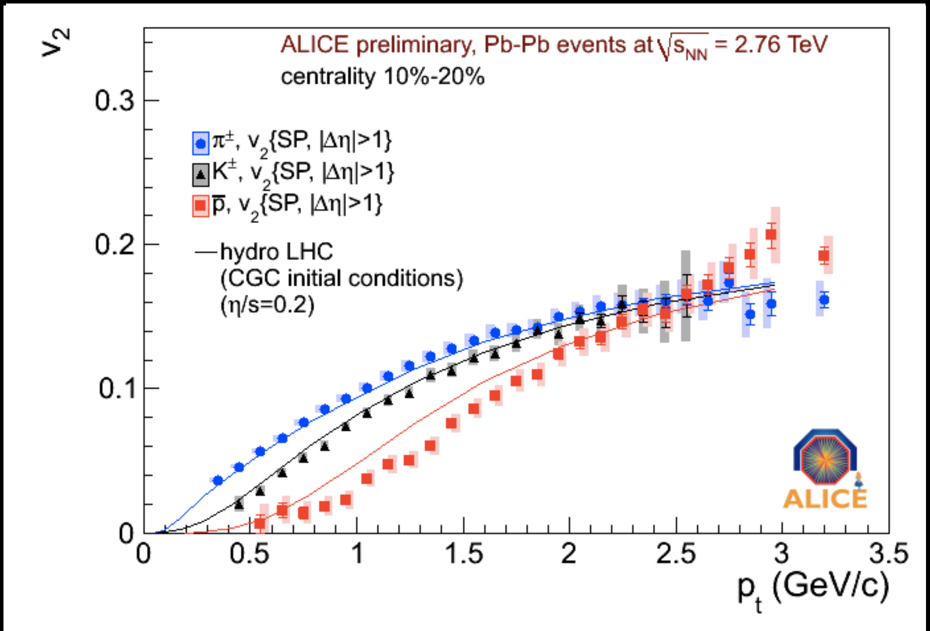


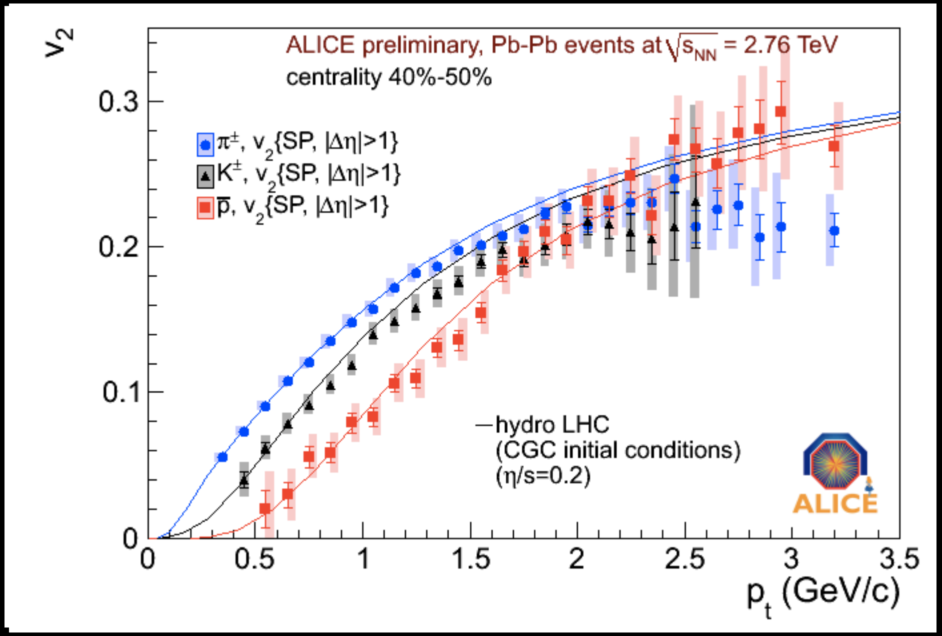
Hydro predicts larger mass-splitting at low p_T at LHC

Mostly due to proton flow, seen in spectra!

LHC Elliptic Flow – Identified Particles

ALICE, M. Krzewicki, R. Snellings, QM 2011





Hydro predicts larger mass-splitting at low p_T

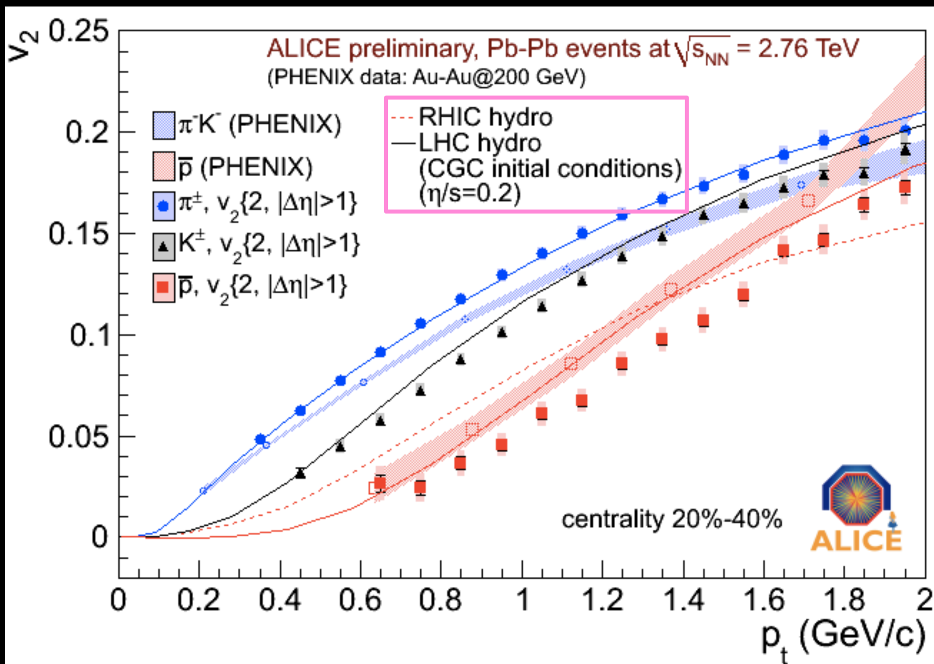
Mostly due to proton flow, seen in spectra!

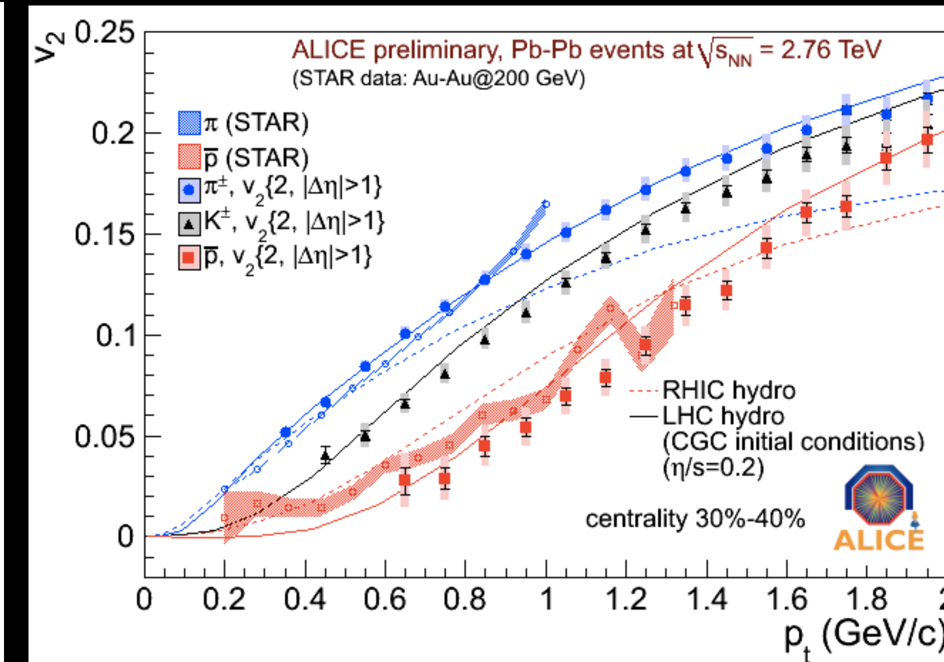
Hydro fits v_2 (π, K) , but NOT the most central $\bar{p}$!

CGC initial conditions, $\eta/s = 0.2$

LHC & RHIC Elliptic Flow – Identified Particles

ALICE, M. Krzewicki, R. Snellings, QM 2011





ALICE (π. K. p) data points

PHENIX bands: Phys. Rev. Lett. 91, 182301 (2003)

STAR bands: Phys. Rev C 77, 054901 (2008)

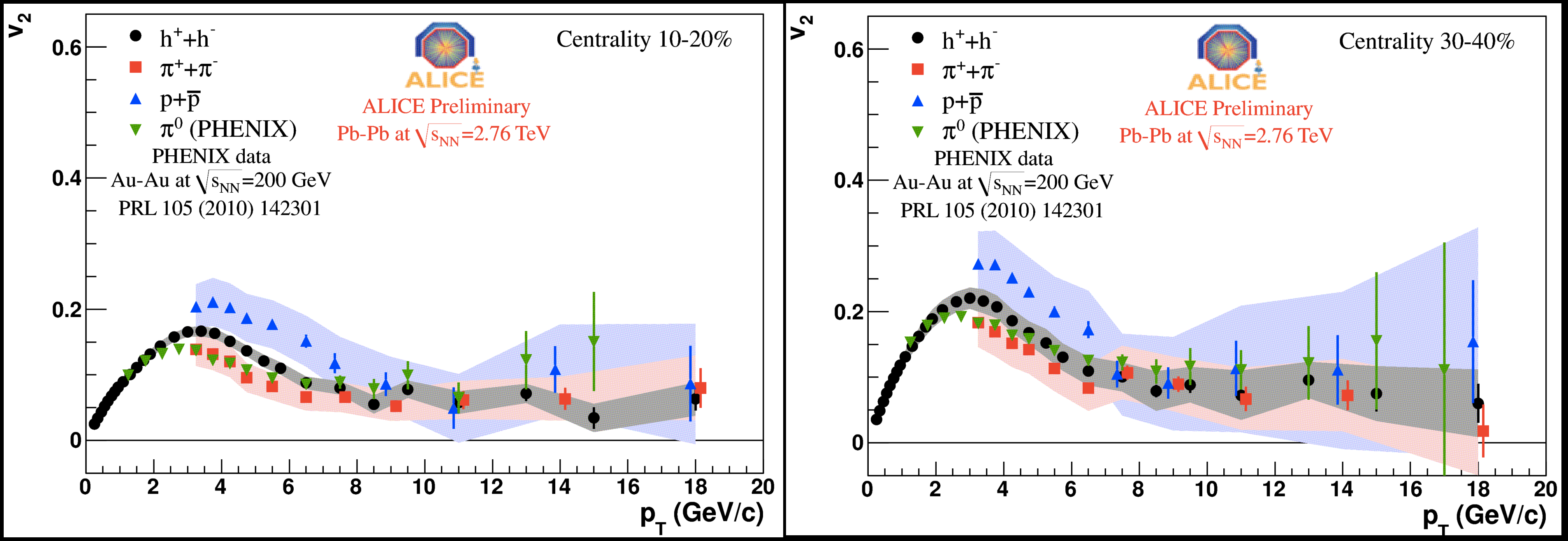
Hydro curves: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

Larger mass splitting at LHC than at RHIC

Hydro: CGC initial conditions, η/s = 0.2

Identified Particle Elliptic Flow at Large p_T

ALICE, A. Dobrin, QM 2011



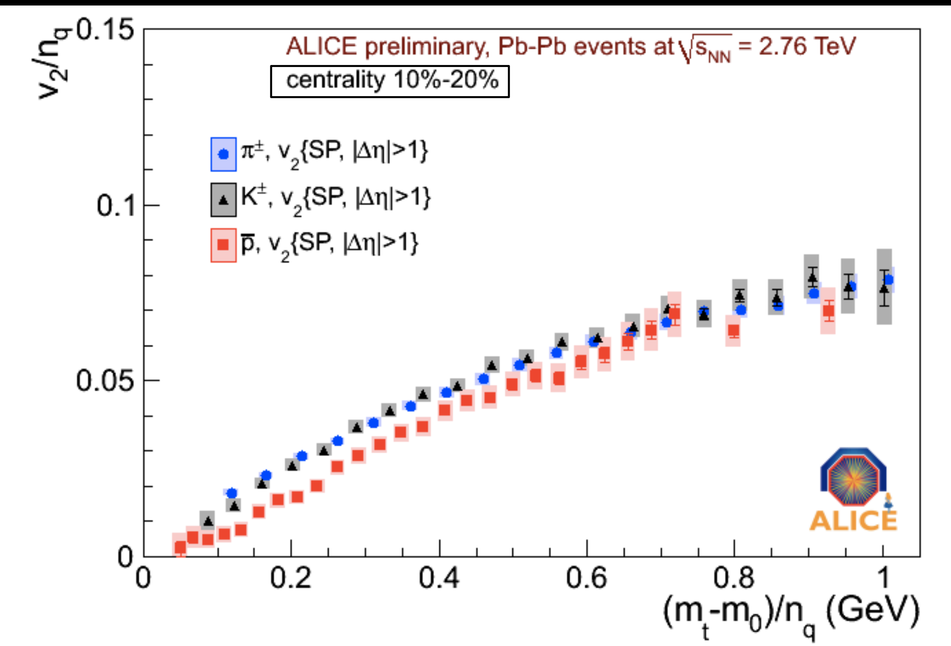
Centrality dependence

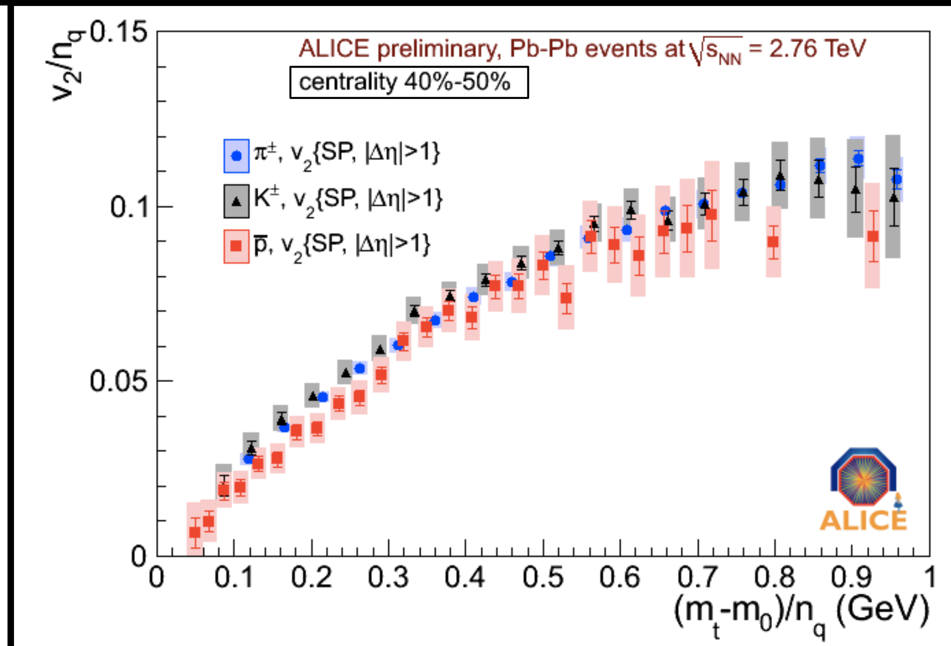
v_2 (p) > v_2 (π) up to ~ 8 GeV/c

PHENIX v_2 (π^0) ~ ALICE v_2 ($\pi^\pm$)

Identified Particle Elliptic Flow – Quark Scaling?

ALICE, M. Krzewicki, R. Snellings, QM 2011





Quark scaling appears to work for π and K at low p_T

Quark scaling does NOT work for protons at low p_T

Quark scaling may work (large errors) for π K p at high p_T

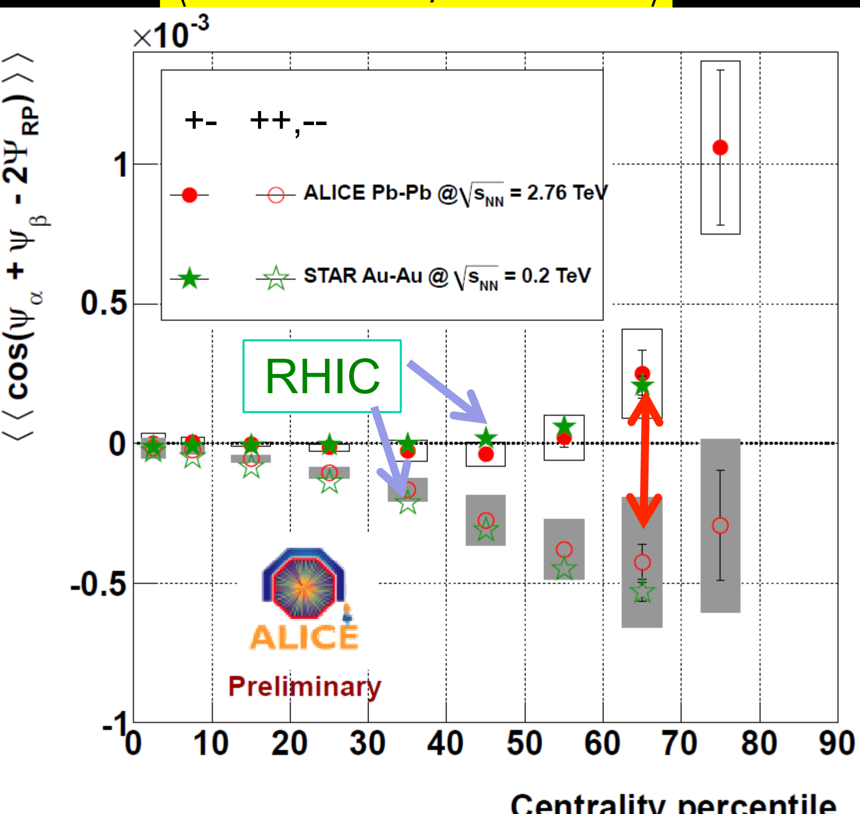
Quick Aside!

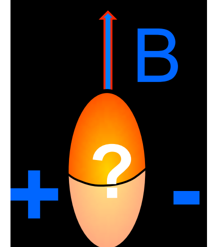
Chiral Magnetic Effect

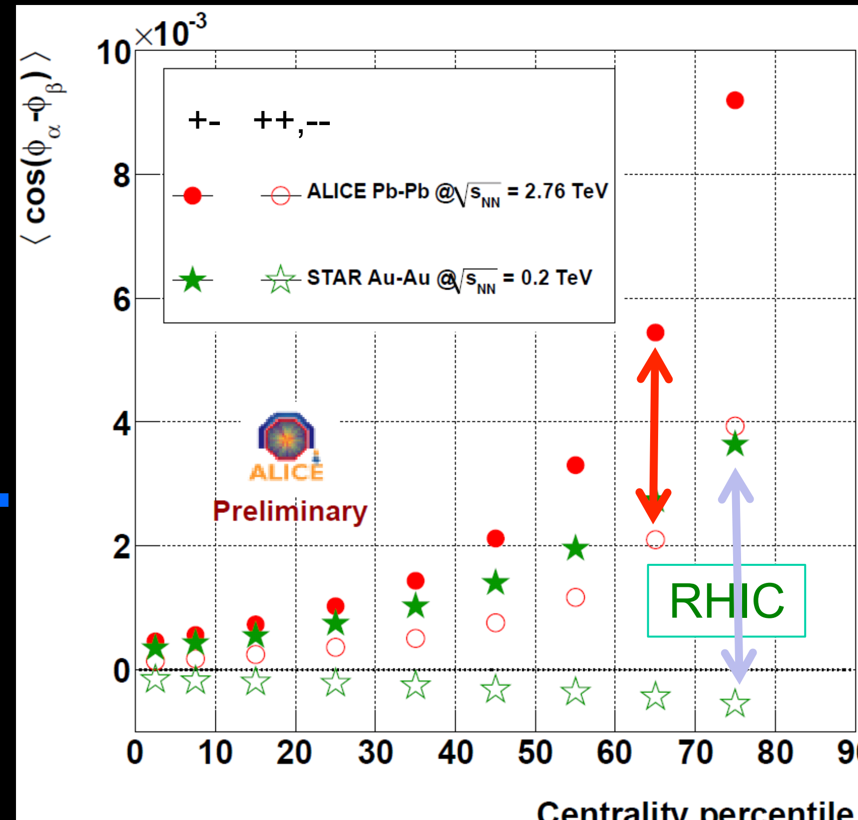
ALICE, J. Schukraft QM 2011

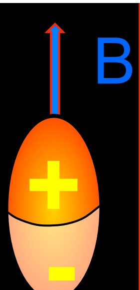
$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$

$\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$









Like sign correlations ->**same side**

Unlike sign correlations **->opposite**

RHIC ≈ LHC

som

Local Parity Violation

in strong magnetic Field ?

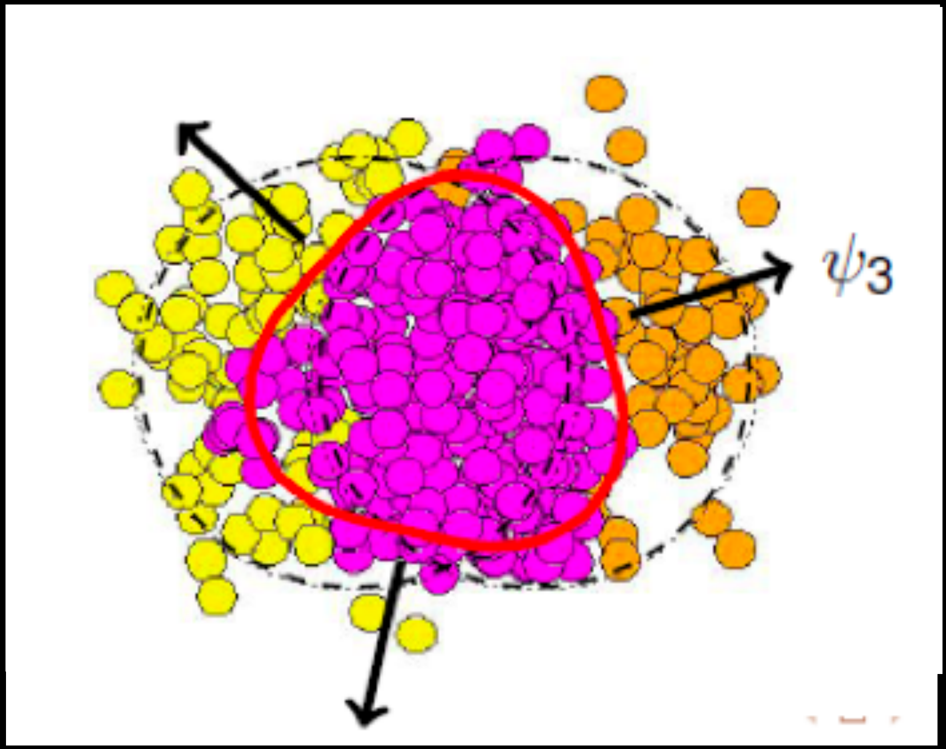
may decrease with √s

RHIC : (++), (+-) unlike sign & magnitude

LHC: (++),(+-) same sign, similar magnitude

Fluctuations & Fourier Decomposition of $dN_{pairs}/d\Delta\phi$

Quick Aside 2!



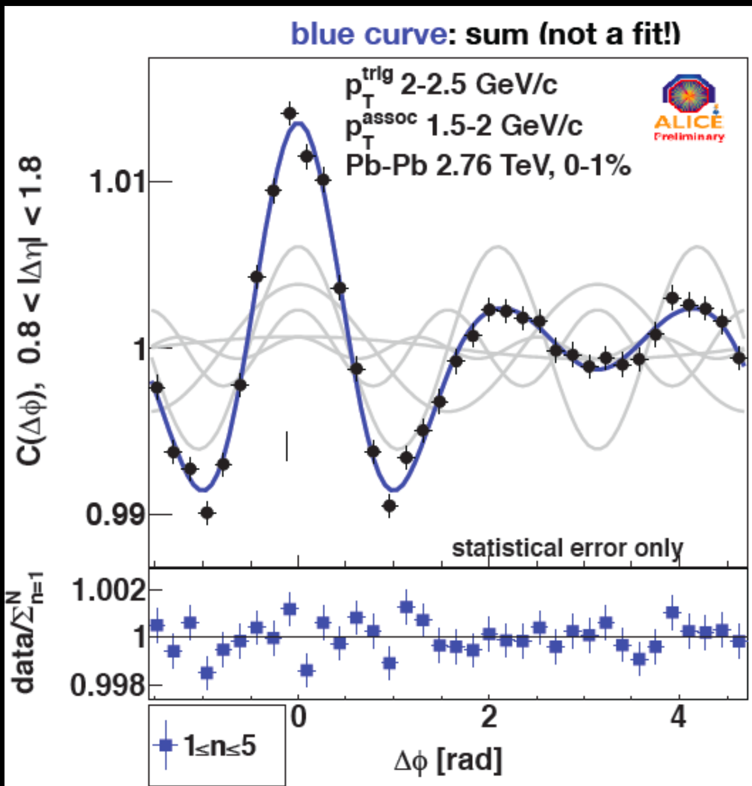
$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \psi_n)$$

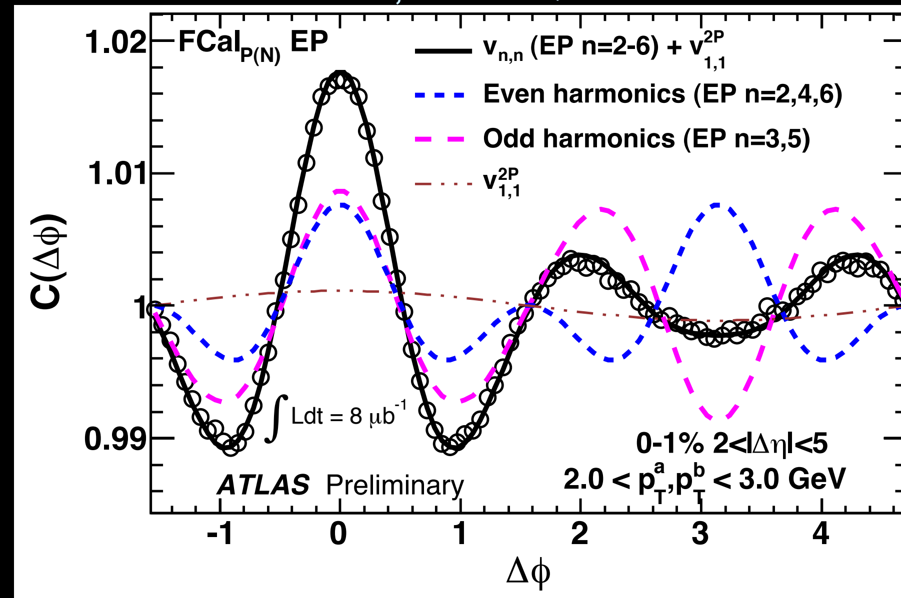
$$\Longrightarrow \left\langle \frac{dN_{\mathrm{pairs}}}{d\Delta\phi} \right\rangle \overset{(\mathrm{flow})}{\propto} 1 + \sum_{n=1}^{\infty} 2 \left\langle {v_n}^2 \right\rangle \cos n(\Delta\phi)$$

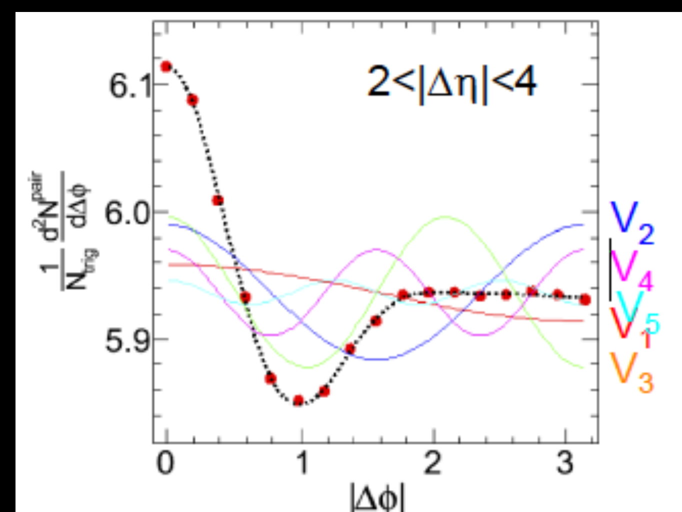
Two-particle Correlations, Fluctuations – Away with the Mach Cone???

ATLAS, J. Jia QM 2011

ALICE, A. Adare QM 2011







CMS, B. Wyslouch QM 2011

v_2 increases from RHIC to the LHC

centrality & p_T dependence of v_2 same at LHC & RHIC
(except decreases below $\sqrt{s_{NN}}$ = 39 GeV)

larger v_2 mass splitting (esp. protons) at LHC
v_2 (p) > v_2 (π) up to ~ 8 GeV/c

v_2 quark scaling does NOT work for protons at LHC

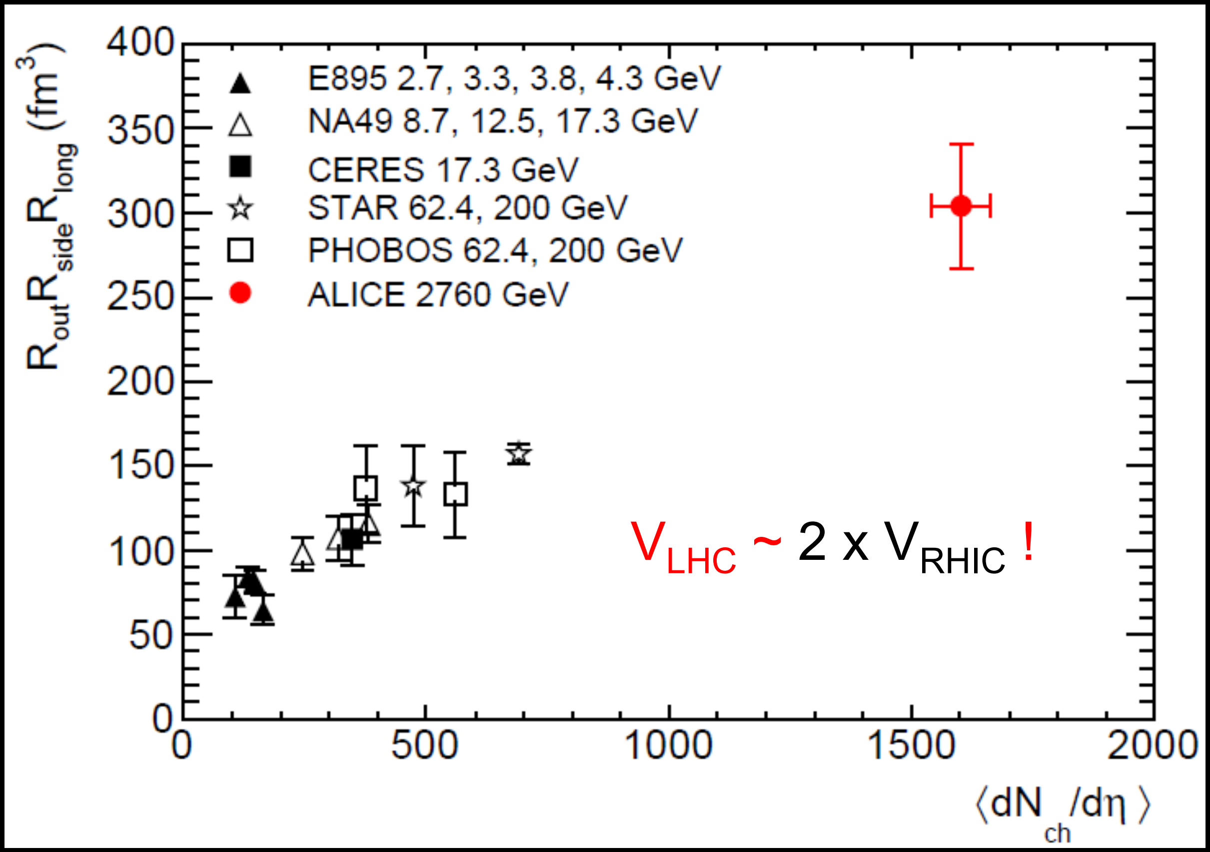
described by viscous hydro with CGC & η/s ~ 0.2

successful Fourier decomposition of bkgd fluctuations!
Chiral magnetic effect (RHIC & LHC similar, also in magnitude)!

Space-time Evolution of System – Freezeout Volume

ALICE, Phys.Lett. B696 (2011) 328
arXiv:1012.4035v2 [nucl-ex] 2011

Bose-Einstein Correlations → $R_{out}R_{side}R_{long}$ → V (homogeneity region)



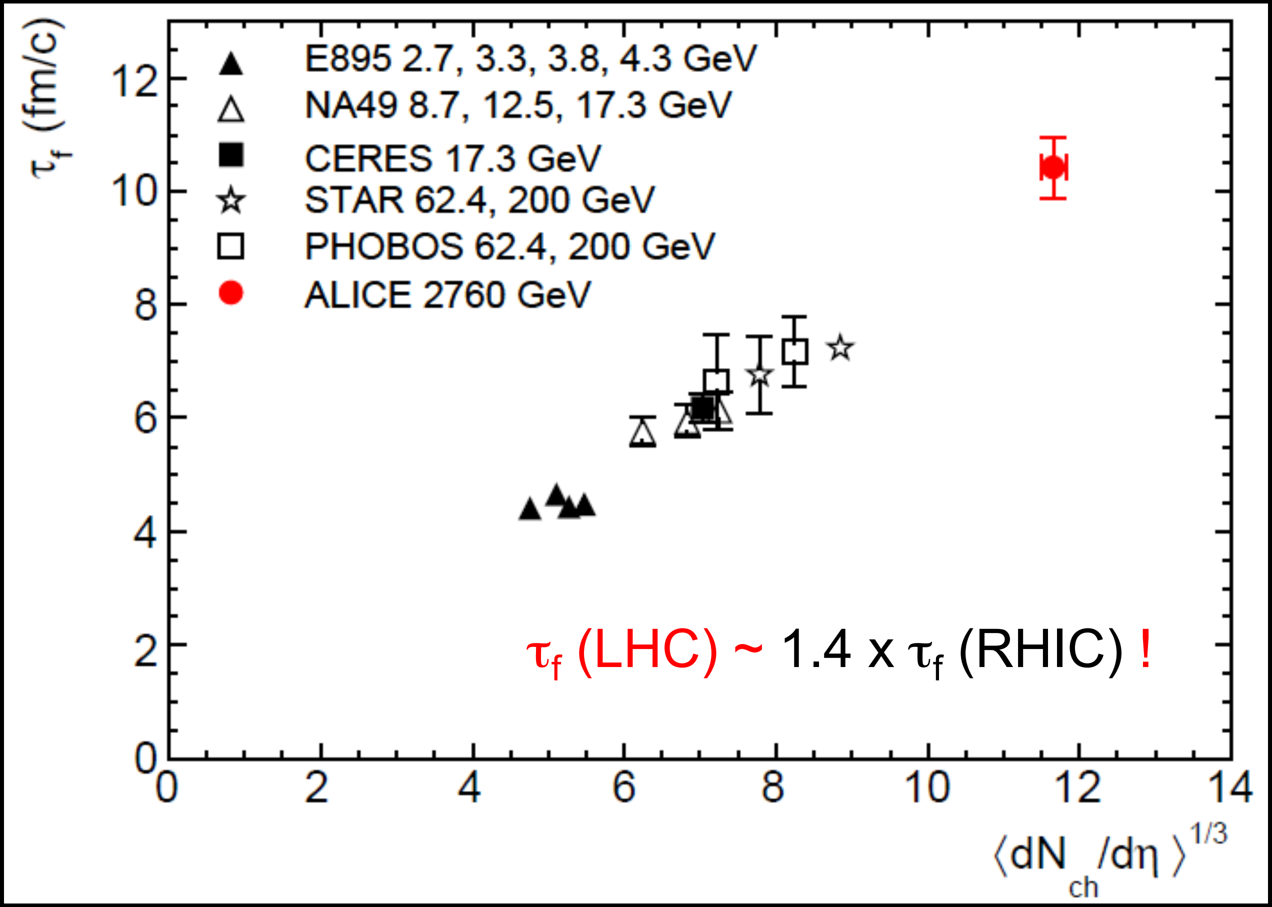
$R_{out}R_{side}R_{long}$ → V (homogeneity region) linear dependence on $dN_{ch}/d\eta$

V (central PbPb) at LHC ~ 300 fm^3

Space-time Evolution of System – Decoupling Time

ALICE, Phys.Lett. B696 (2011) 328
arXiv:1012.4035v2 [nucl-ex] 2011

Bose-Einstein Correlations → Decoupling time τ_f → $\tau_f \sim R_{long}$



$\tau_f \sim \langle dN_{ch}/d\eta \rangle^{1/3}$ τ_f (central PbPb) ~ 10 – 11 fm/c

Hydrodynamic Evolution of System

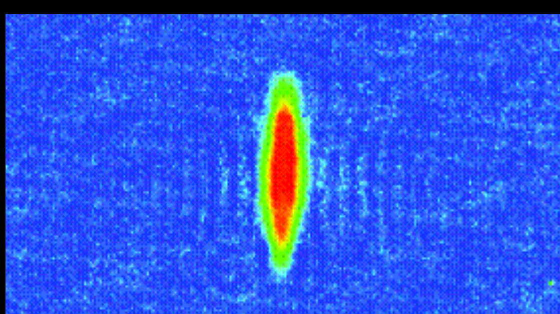
C. Shen, QM 2011

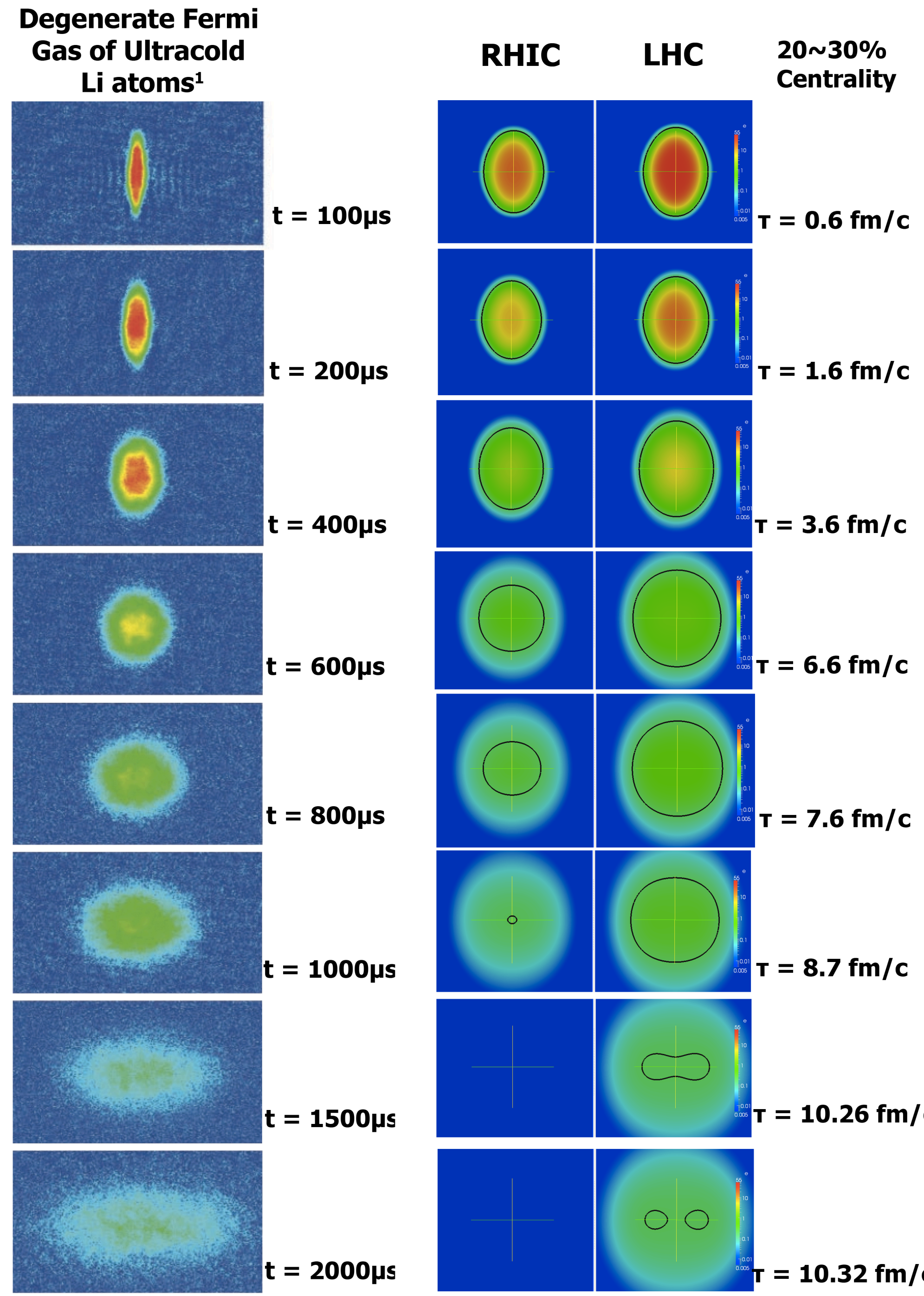
Ref: C. Shen, U. Heinz, P. Huovinen, H. Song, arXiv:1105.3226.

Hydro evolution at RHIC and LHC: 20-30% peripheral AuAu or PbPb

Black curves: freeze out surface at $T_{kin\ FO}$= 120MeV

LHC **expansion rate >>** RHIC rate
- Stronger hydro force -> **more v_2**
- Rips apart fireball (in two) along the reaction plane near FO!





Pb-Pb collisions at the LHC have:

volume ~ 300 fm^3

lifetime ~ 10 fm/c

That is

2 × volume

1.4 × lifetime

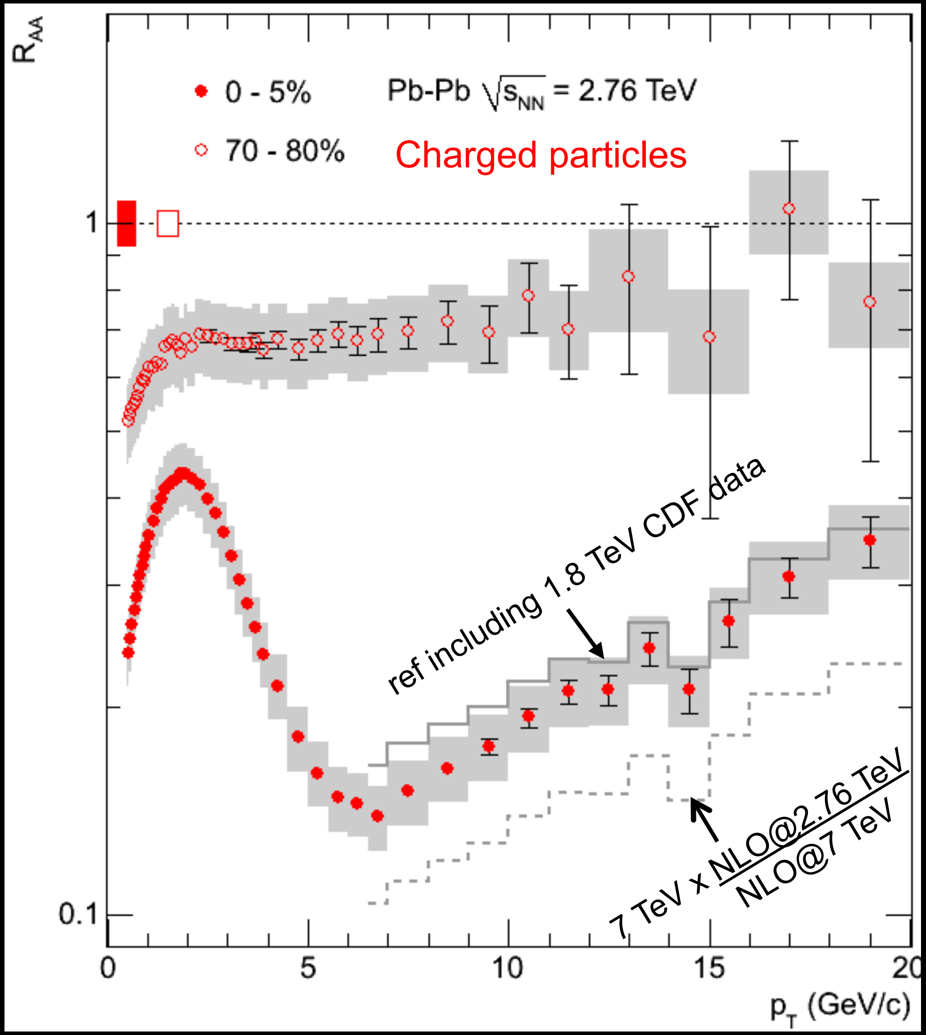
compared to RHIC collisions!

Hard Probes with Heavy Ions at the LHC

Part 1 – R_{AA} (particles)

LHC – Central Pb-Pb Spectra Suppressed

ALICE, Phys. Lett. B 696 (2011) 30.



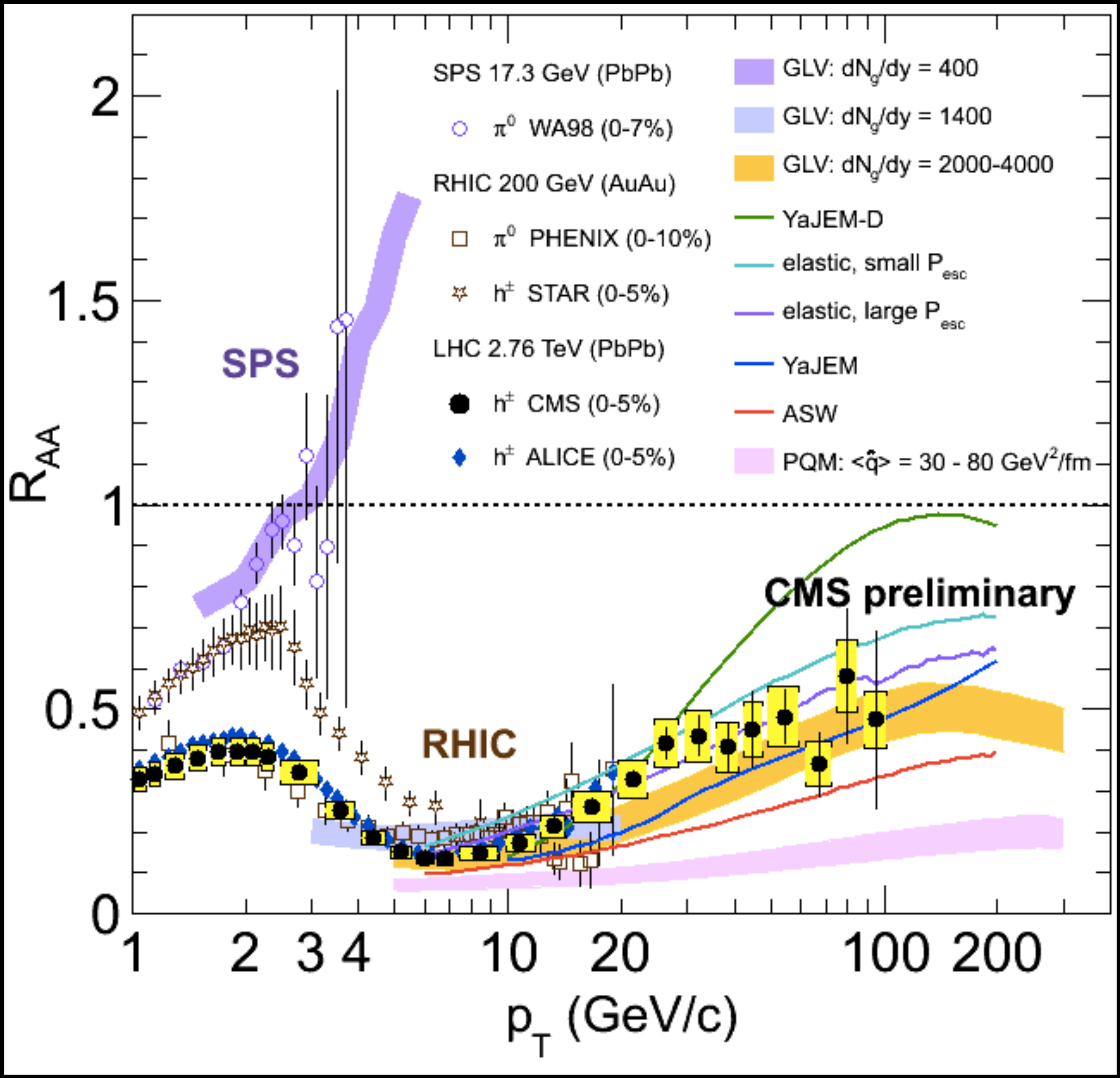
$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta dp_T}$$

Central Pb-Pb suppressed!

Peripheral Pb-Pb less!

R_{AA} at SPS, RHIC, LHC, & Theories

CMS, Wyslouch QM 2011

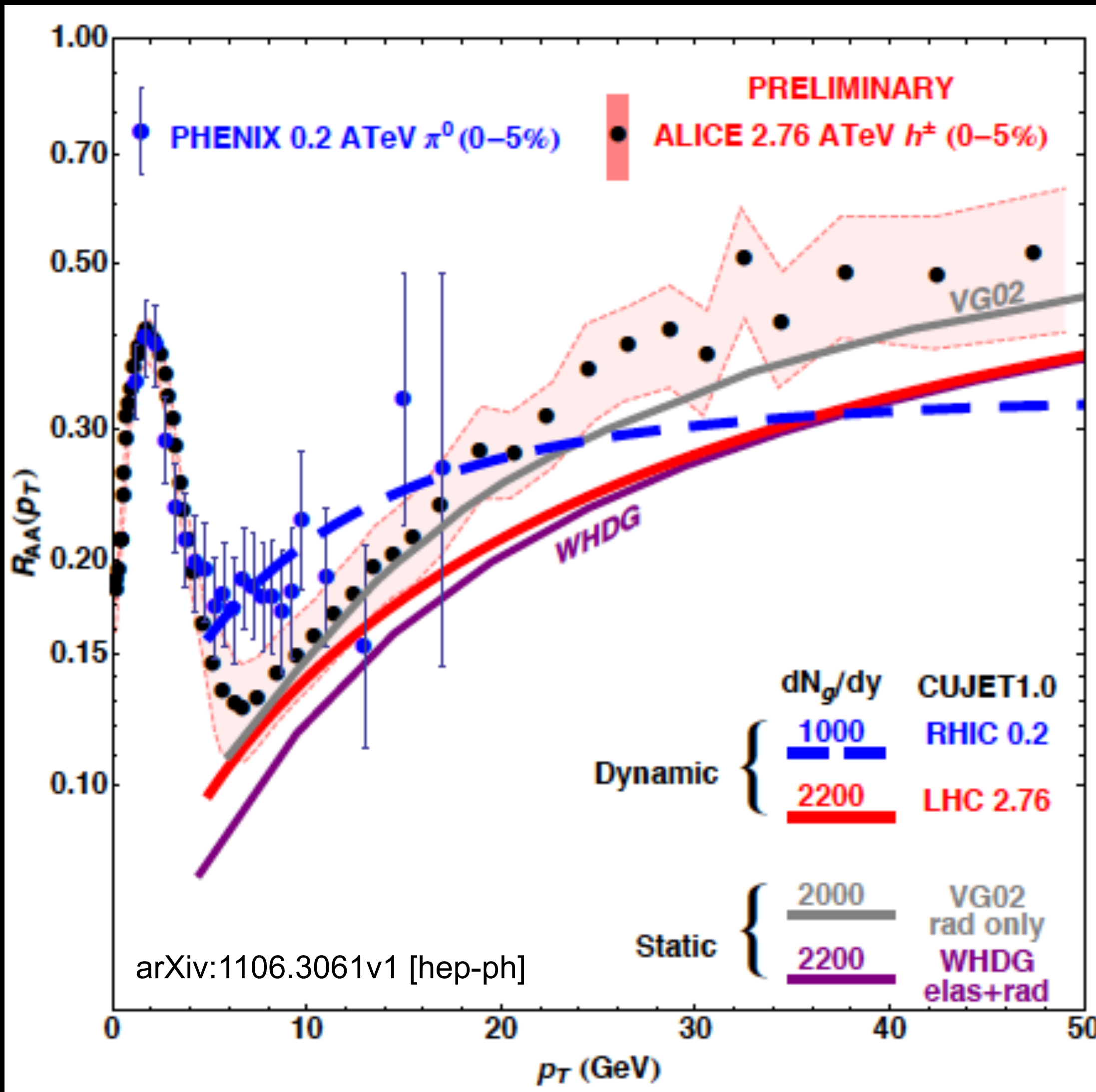


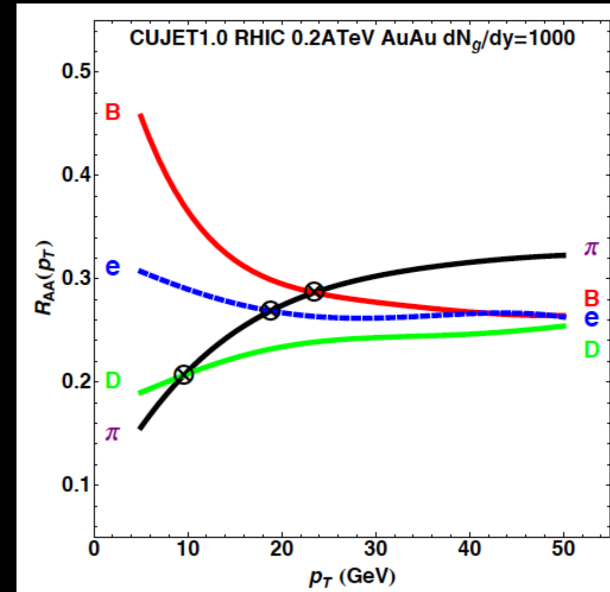
R_{AA} to 100 GeV/c!

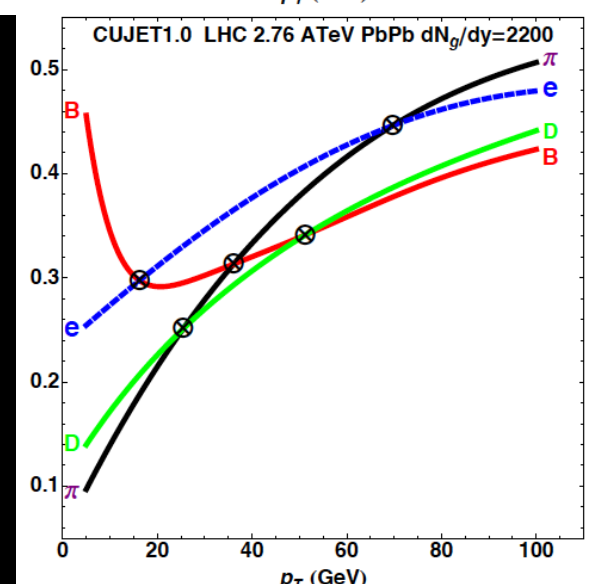
Large quenching!

More R_{AA} from RHIC, LHC and Theory

A. Buzzatti & M. Gyulassy, arXiv:1106.3061v1



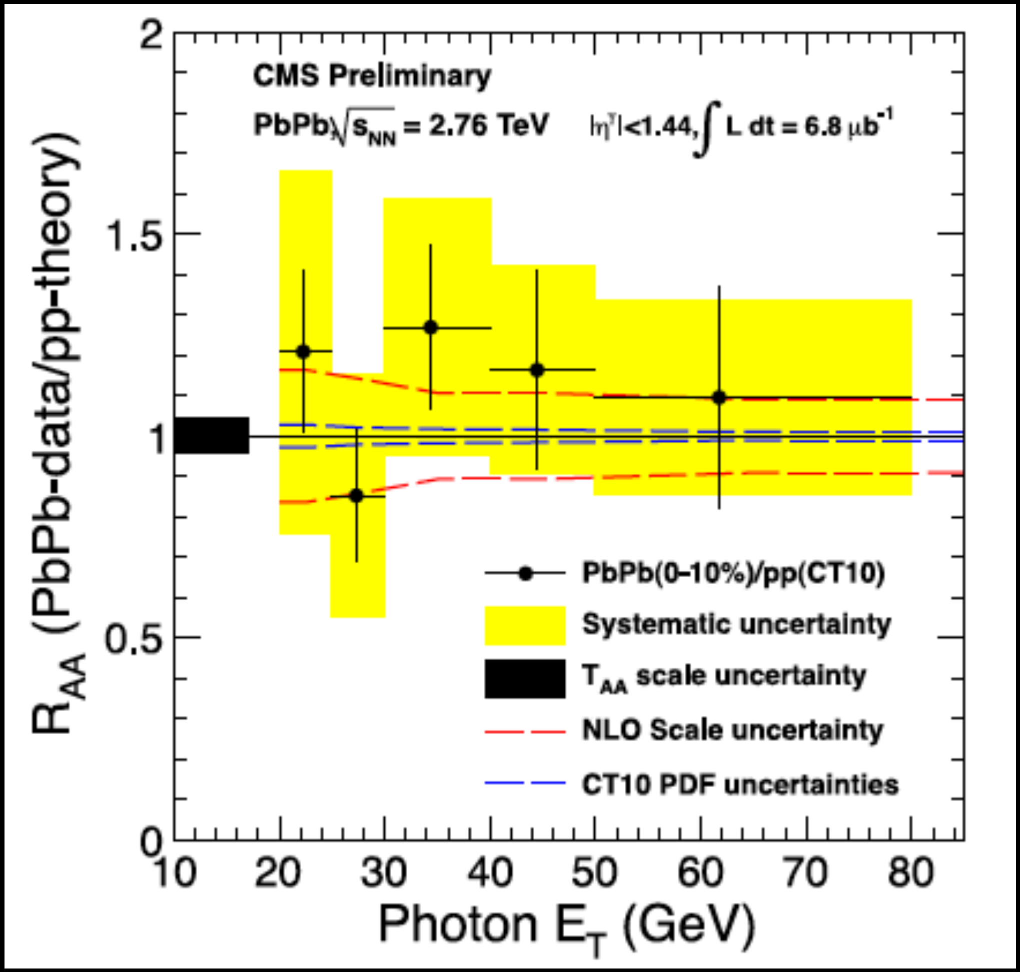


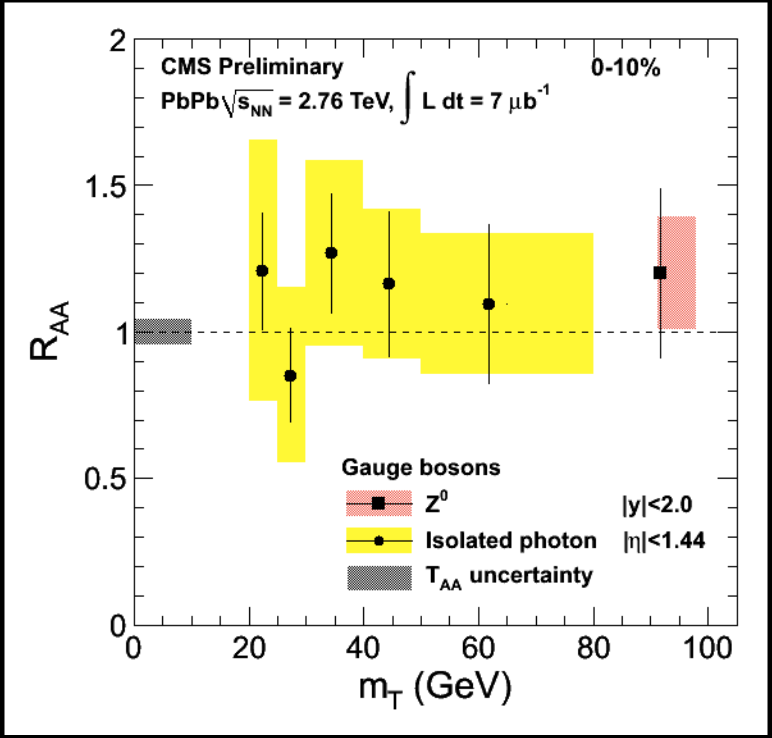


Note π,D,B crossing patterns!

R_{AA} for Colorless Probes

CMS, Y.J. Lee QM 2011

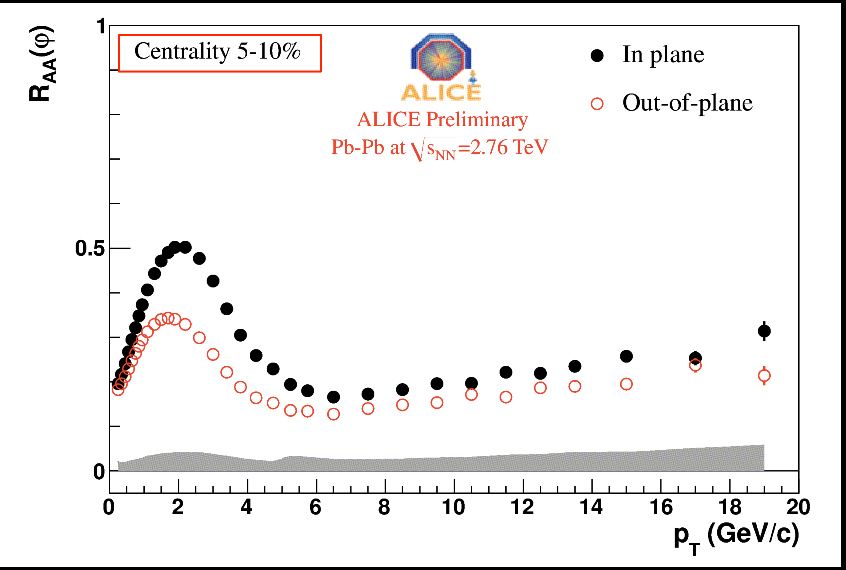


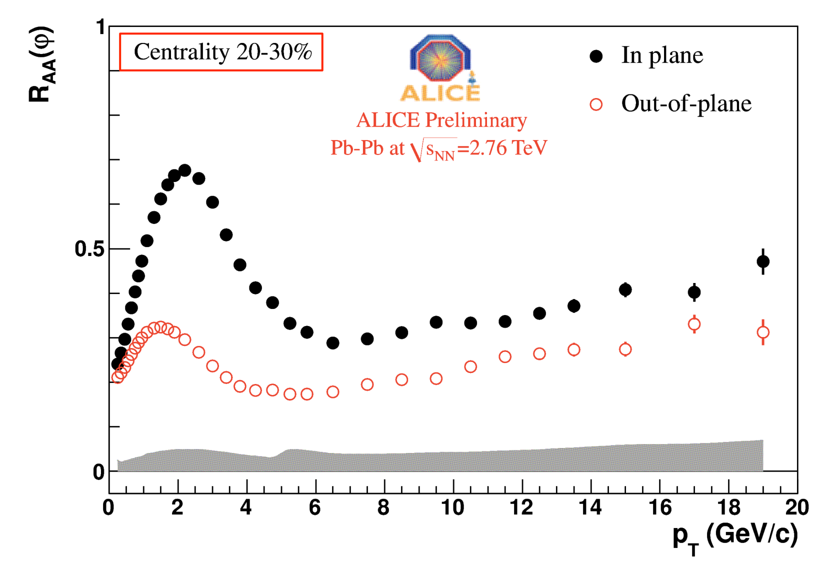


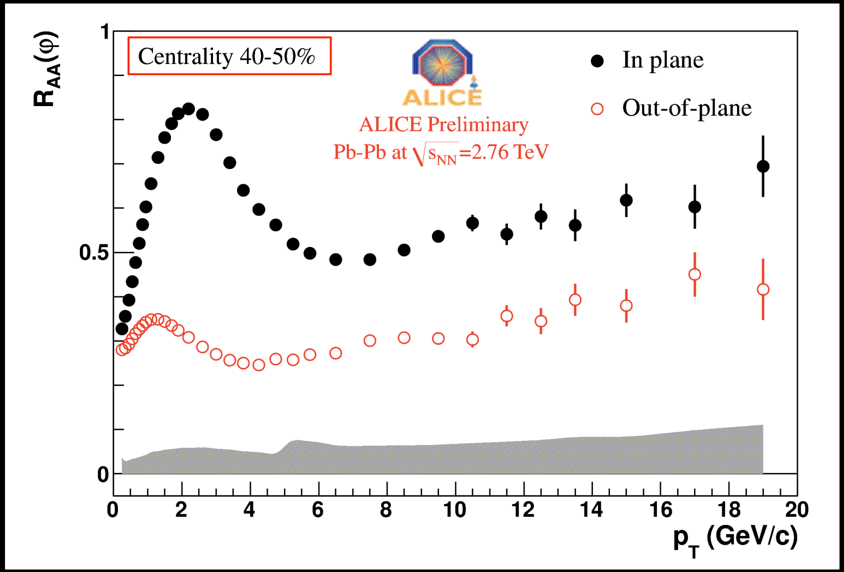
R_{AA} consistent with 1 within uncertainties!

Charged Particle R_{AA} Relative to Reaction Plane

ALICE, A. Dobrin QM 2011







More suppression out of plane (longer path-length)!

Difference increases with increase in aspect ratio of initial overlap!

R_{AA} for Heavy Quarks!

ALICE, A. Dainese QM 2011

Parton Energy Loss through

medium-induced gluon radiation

and collisions with medium

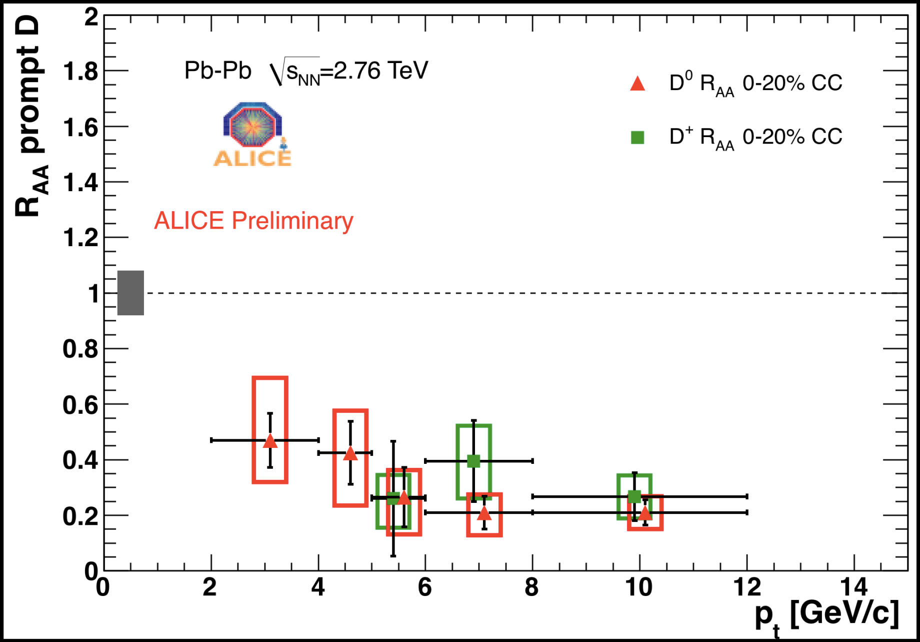
From pQCD expect:

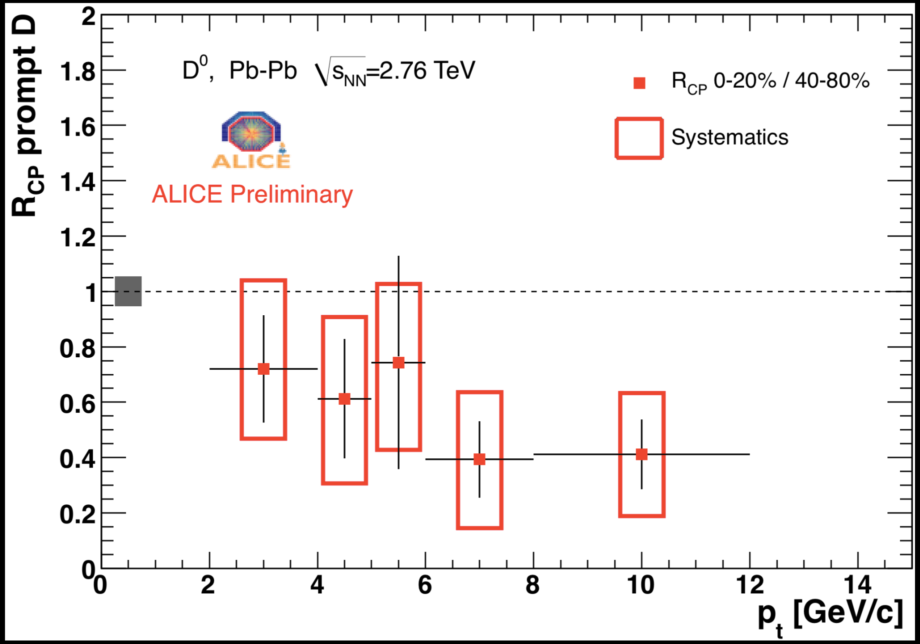
$$\Delta E_g > \Delta E_{q,c} > \Delta E_b$$

and thus:

$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$$

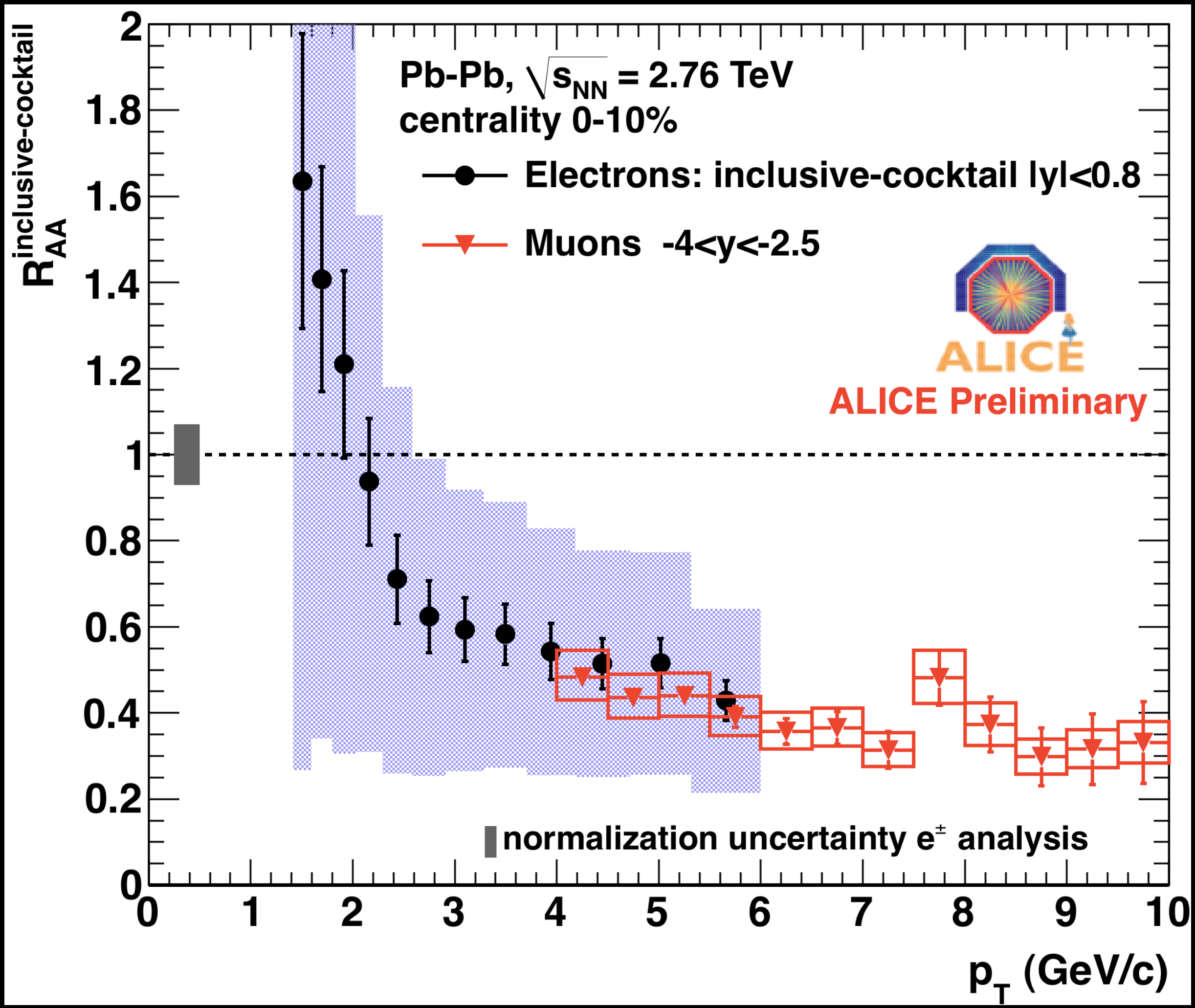
Observed R_{AA} of D-mesons strongly suppressed (like pions)!





R_{AA} for e and μ from Heavy Quarks!

ALICE, A. Dainese QM 2011



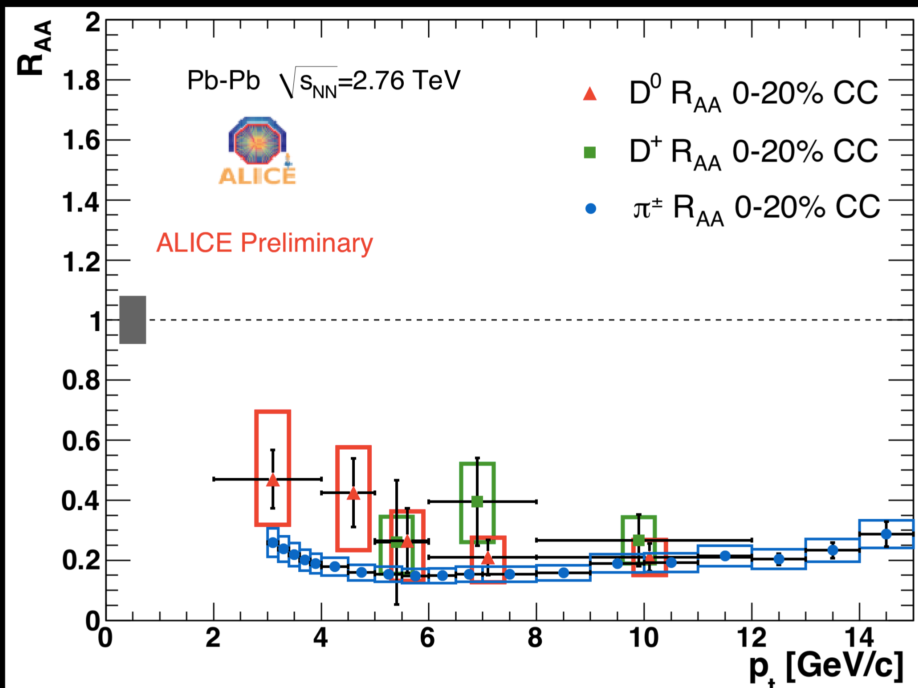
R_{AA} of electrons and muons are consistent within errors.

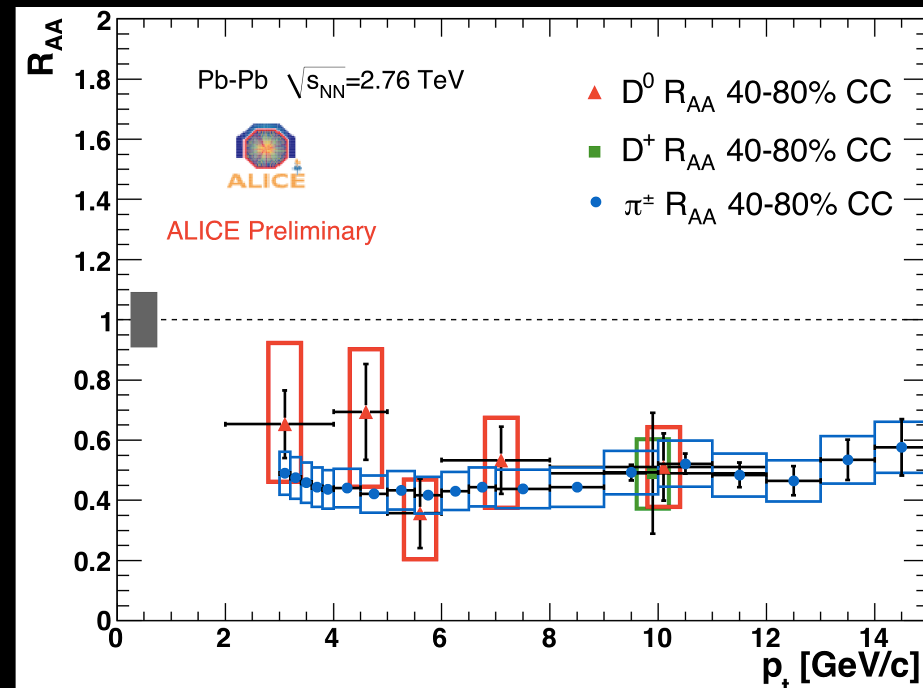
From FONL:
B-decays dominate above ~ 5-6 GeV/c.

Thus:
B suppression appears to be large!

R_{AA} Centrality Dependence – D and π

ALICE, A. Dainese QM 2011





0 – 20 % centrality

40 – 80 % centrality

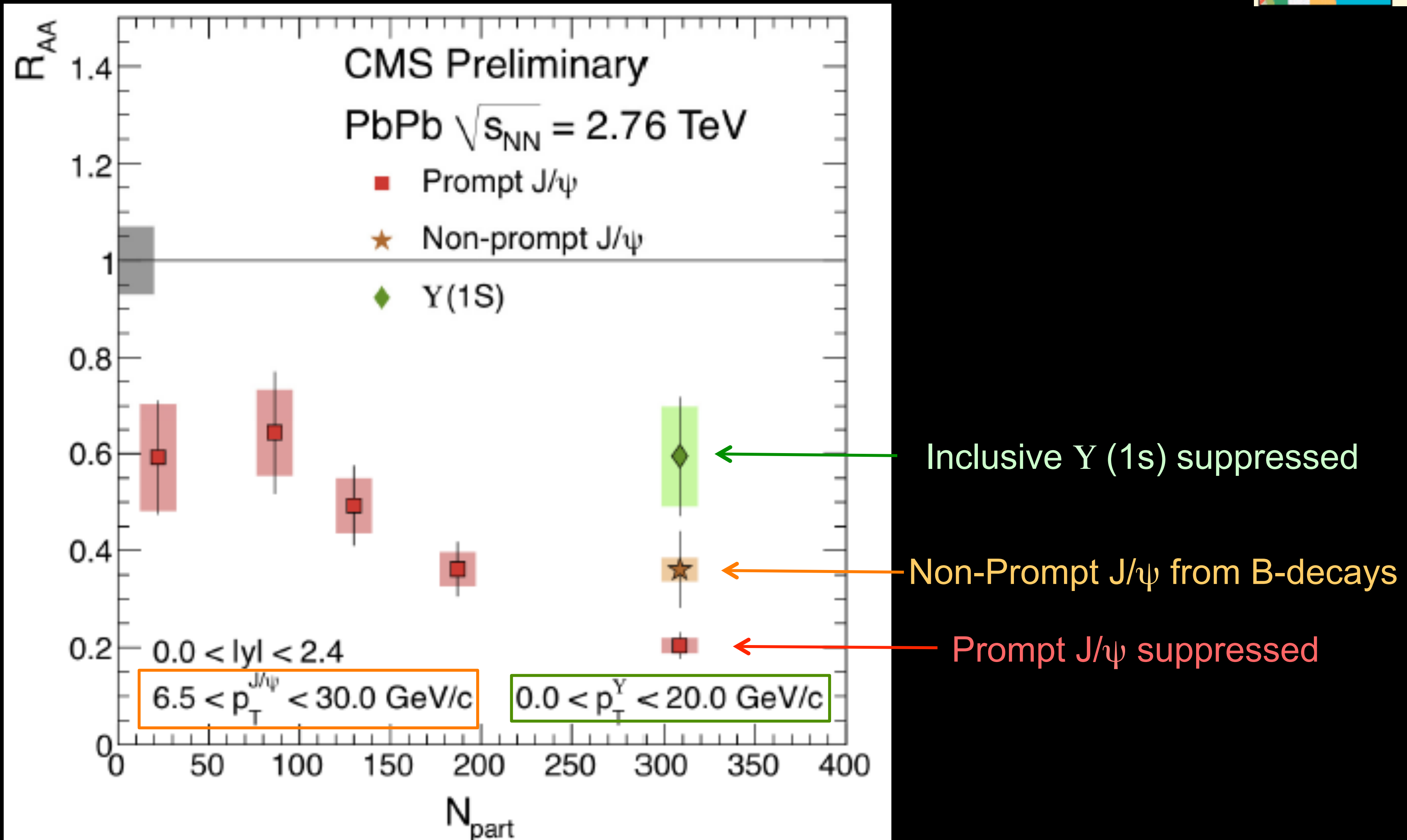
~ 4-5x suppression for charm for p_T > 5 GeV/c

R_{AA} (D) ~ R_{AA} (π) for p_T > 5 GeV/c

R_{AA} (D) slightly larger than R_{AA} (π) for p_T < 5 GeV/c

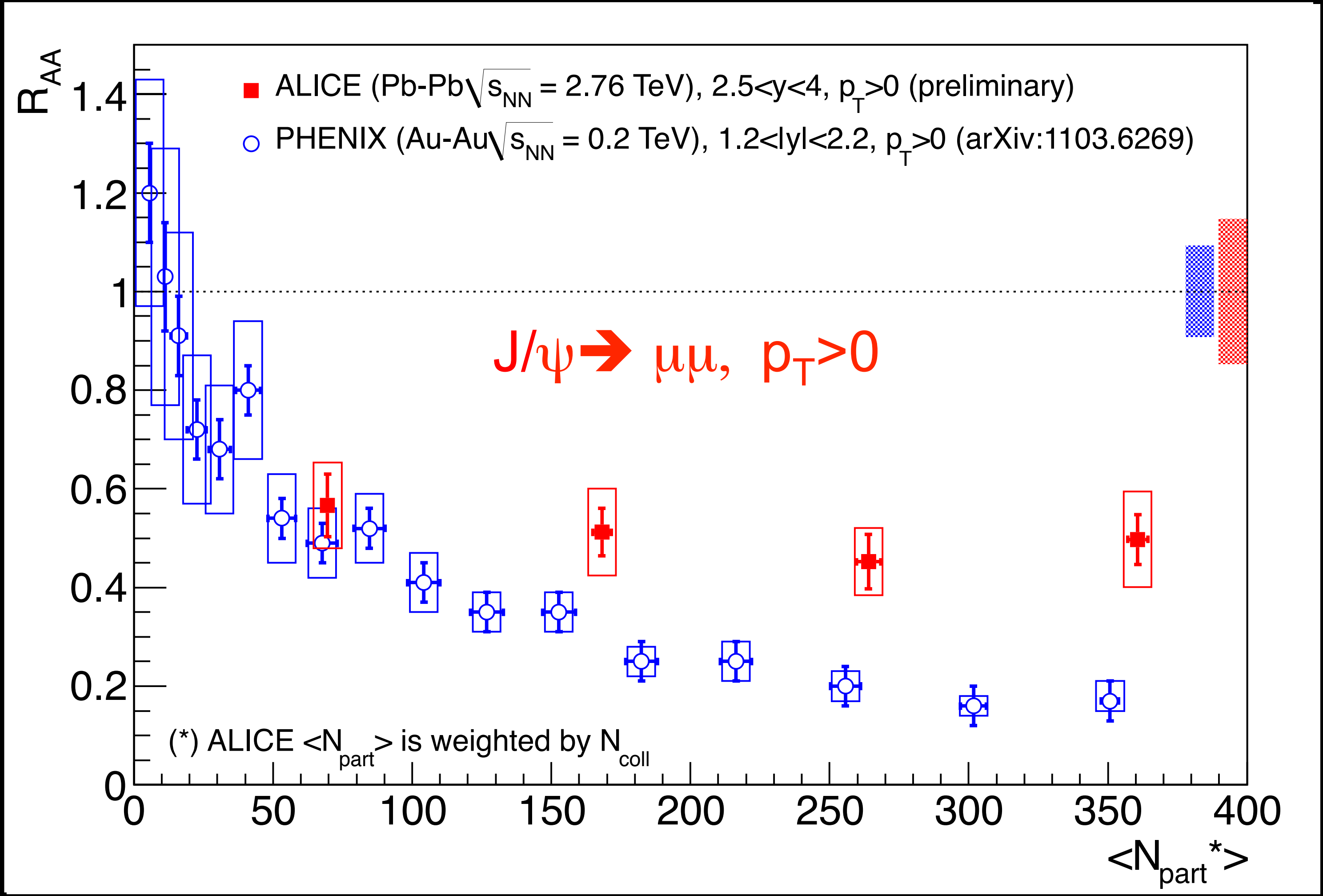
R_{AA} Centrality Dependence – J/ψ and ϒ

CMS, C. Sylvestre, B. Wyslouch QM 2011



J/ψ R_{AA} Centrality Dependence – LHC & RHIC

ALICE, G. Martinez-Garcia QM 2011



J/ψ R_{AA} larger at LHC (2.5<y<4) than at RHIC (1.2<|y|<2.2)

Similar to RHIC (|y|<0.35), except for most central bin

Note – $dN_{ch}/d\eta(N_{part})^{LHC} \sim 2.1 \times dN_{ch}/d\eta(N_{part})^{RHIC}$

Pb-Pb collisions at the LHC have:

large quenching to high pT

R_{AA} pathlength differences as expected

D suppression large (R_{AA} ~ 0.2-0.3 in central)

B suppression large (R_{AA} ~ 0.3-0.4 in central)

Prompt J/ψ suppression large (R_{AA} ~ 0.2 in central)

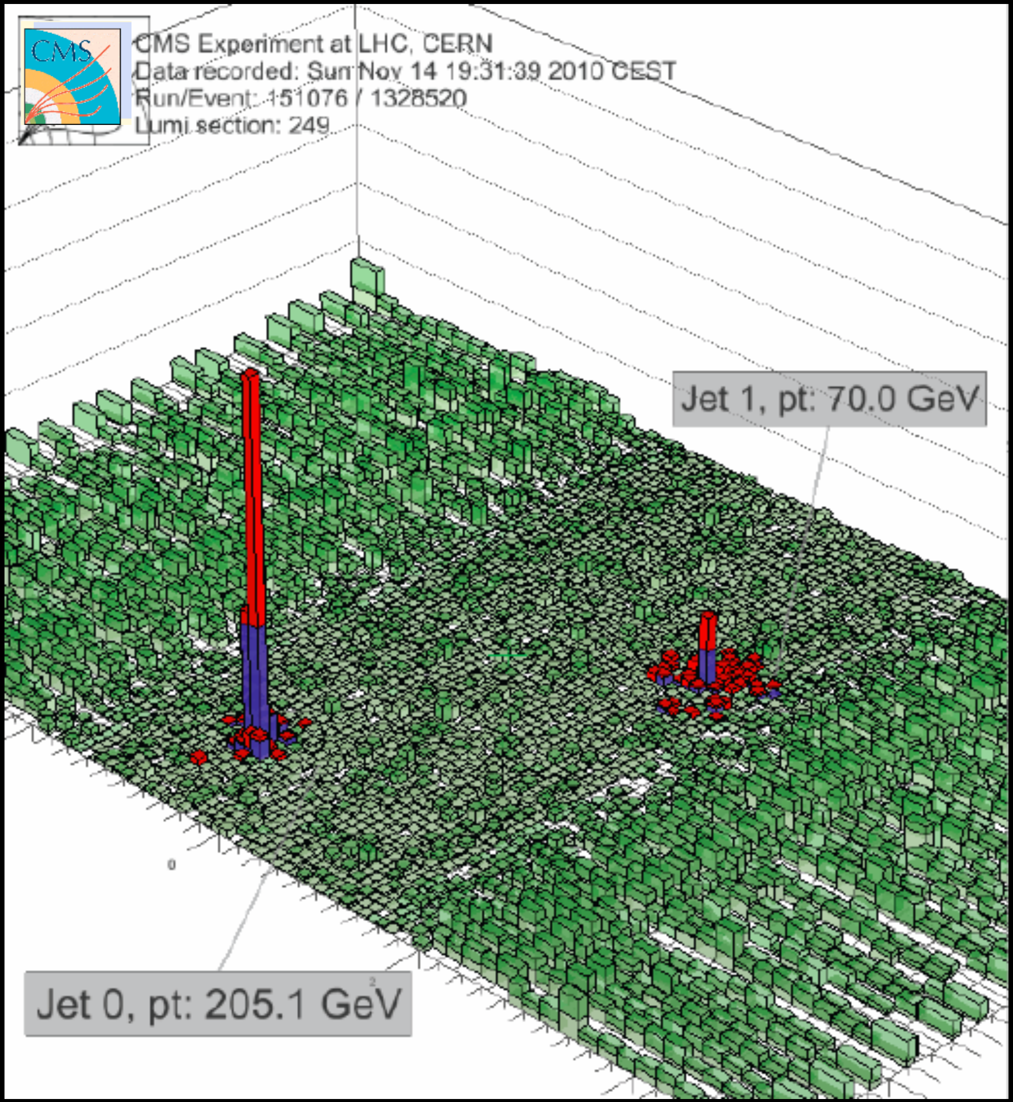
Υ(1s) suppressed (R_{AA} ~ 0.6 in central)

Forward prompt J/ψ less suppressed than at RHIC

Theory predictions of unique $R_{AA}(p_T)$ differences for π, D, B

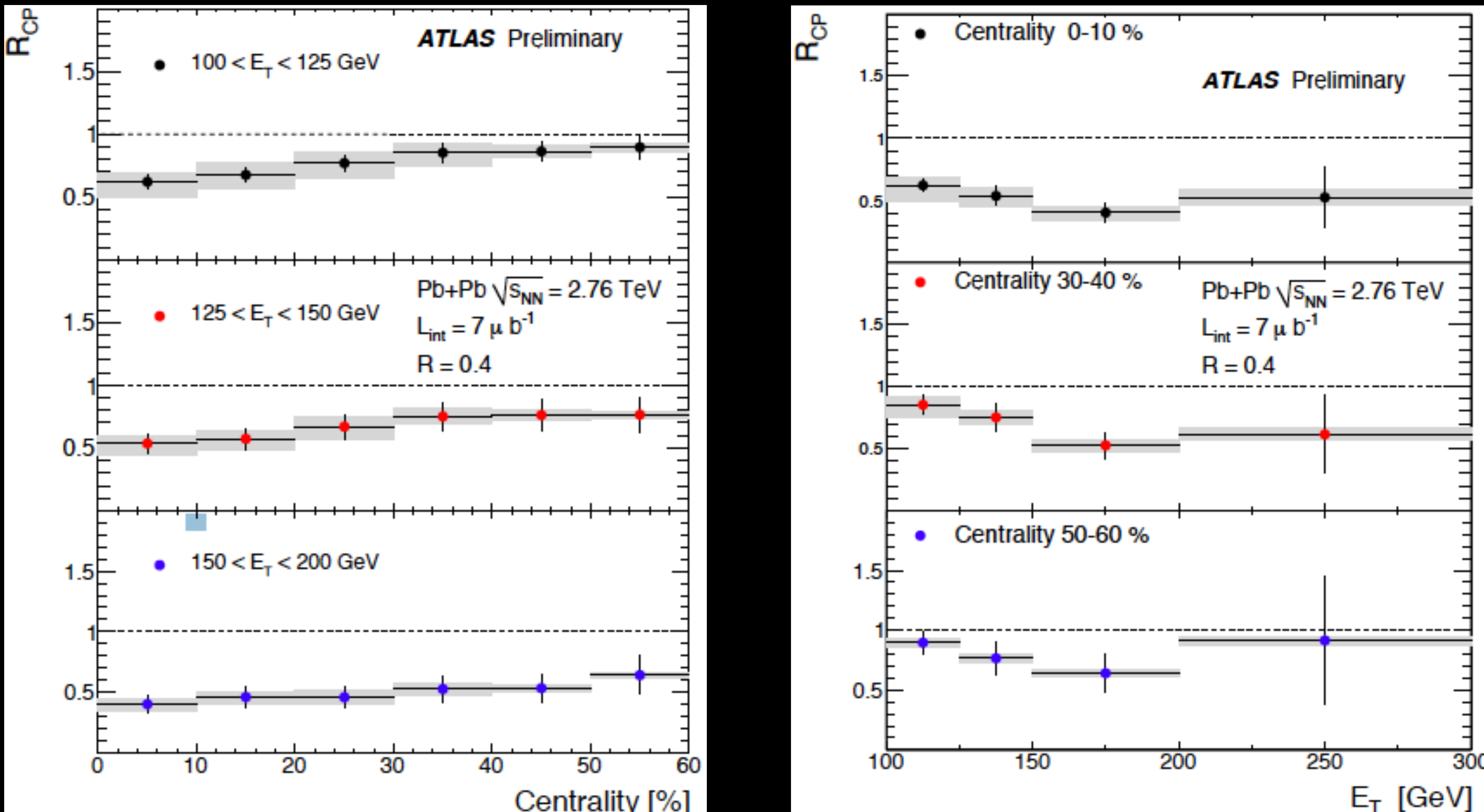
Hard Probes with Heavy Ions at the LHC

Part 2 – Jets



Jet Suppression at the LHC – ATLAS

ATLAS, B. Cole QM 2011



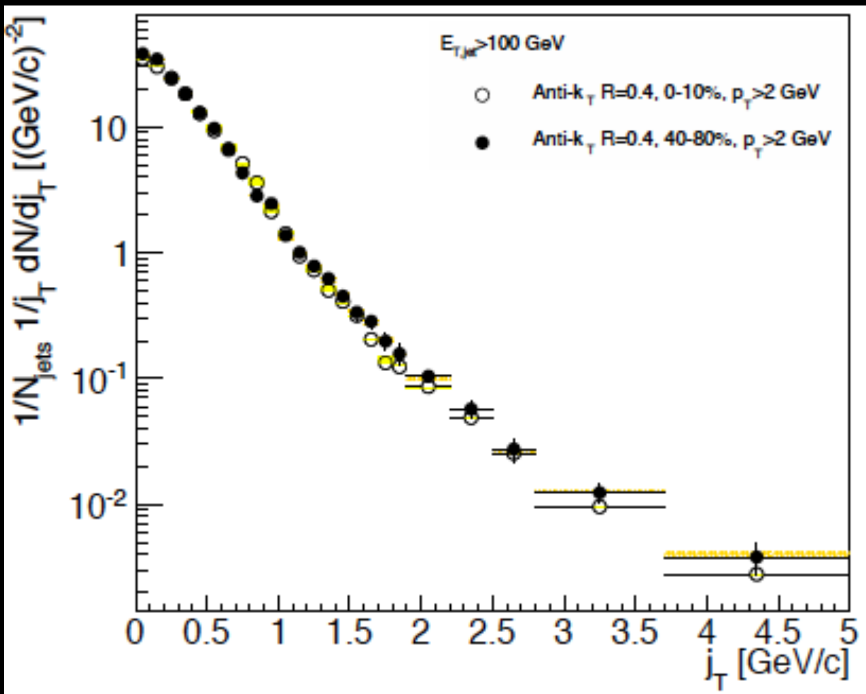
Similar jet suppression R_{CP} (rel to 60–80% centrality):

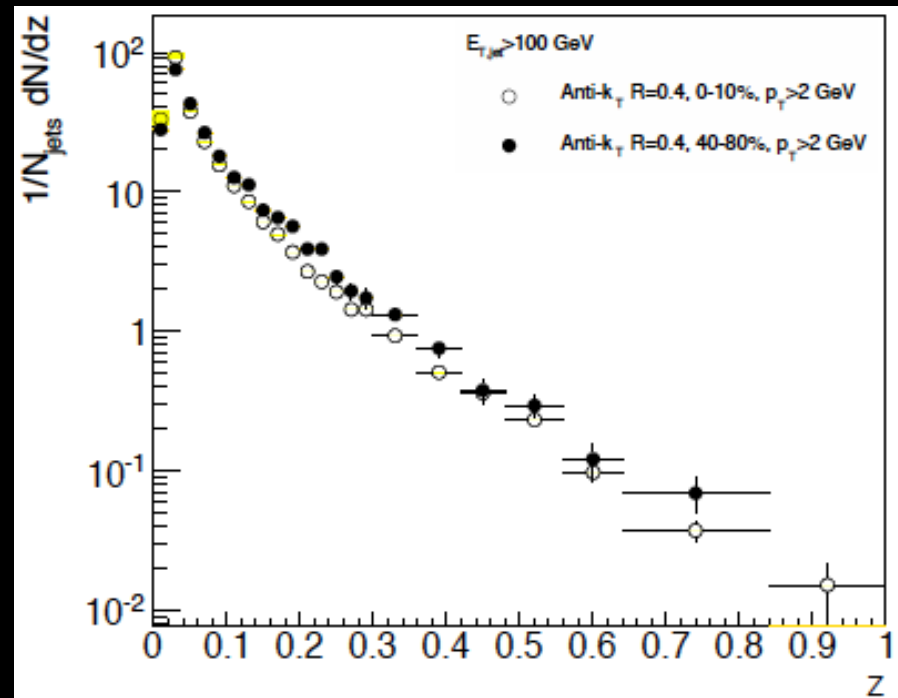
increases with centrality (to factor 2)

no significant jet E_T dependence

Jet "Shapes" at the LHC – ATLAS

ATLAS, B. Cole QM 2011





j_T = p_T(hadron) x sin ($R_{\eta\phi}$)

z = p_T(hadron) / E_T x cos ($R_{\eta\phi}$)

For central vs peripheral:

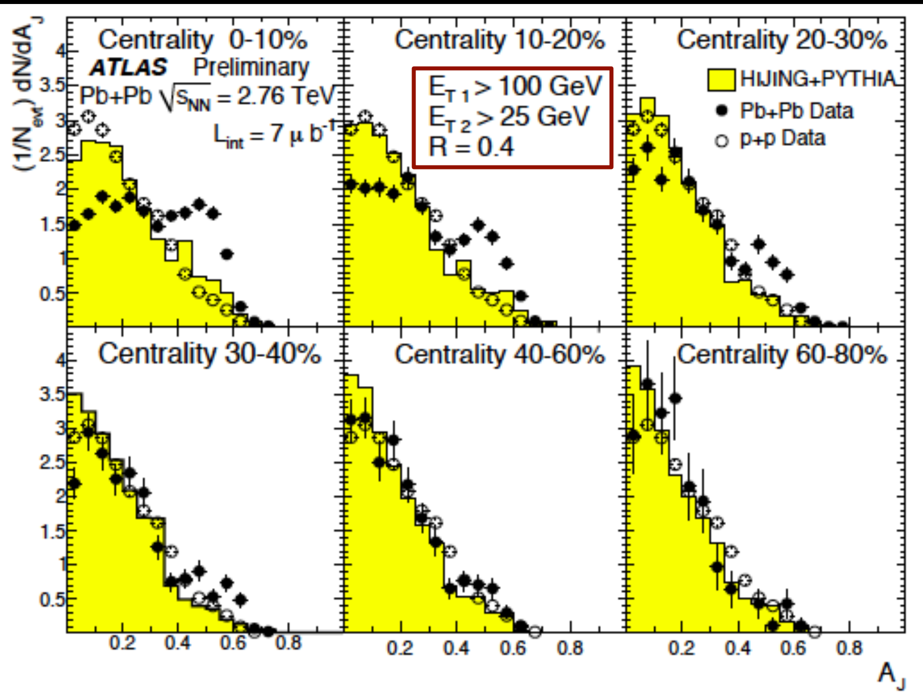
No significant broadening of jet fragment j_T distn's.

For central vs peripheral:

Slight softening of jet fragment z distn's.

Di-Jet Asymmetries at the LHC – ATLAS

ATLAS, B. Cole QM 2011

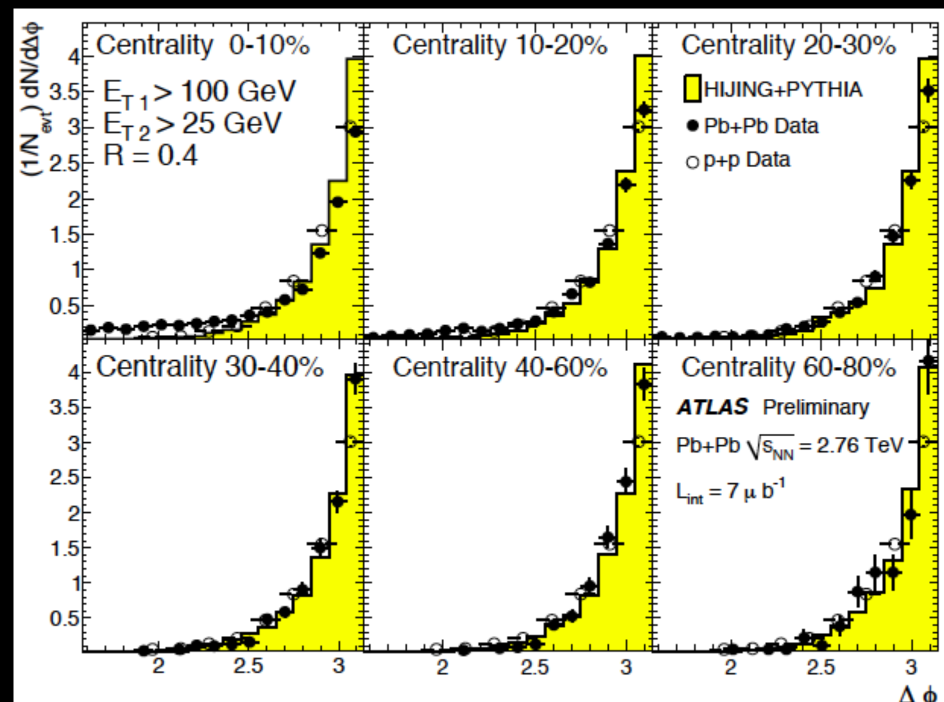


Di-jet energy imbalance

$$A_J = (E_{T1} - E_{T2}) / (E_{T1} + E_{T2})$$

Corrected for underlying event flow

Also results for R = 0.2

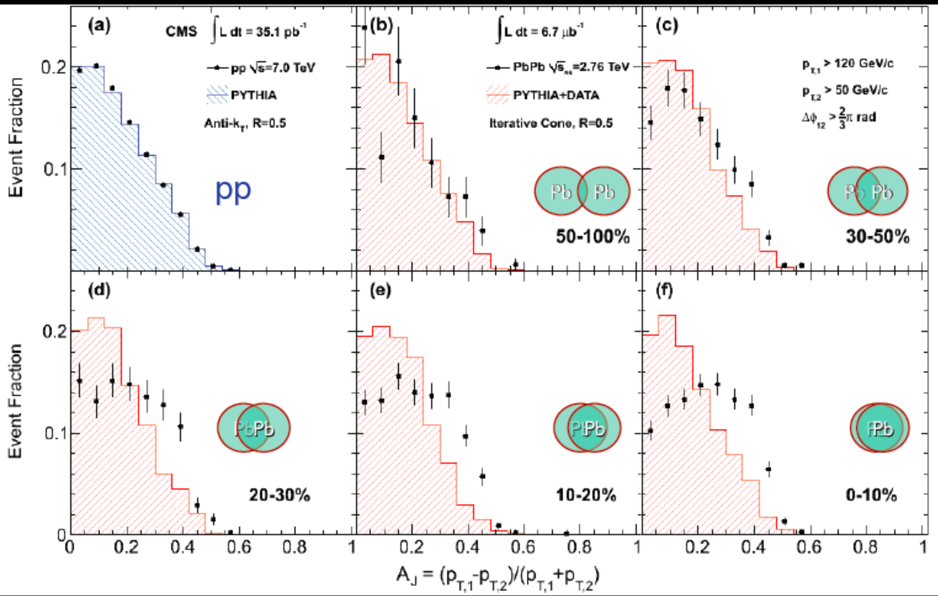


Also see: ATLAS, PRL 105 (2010) 252303

Little di-jet asymmetry observed

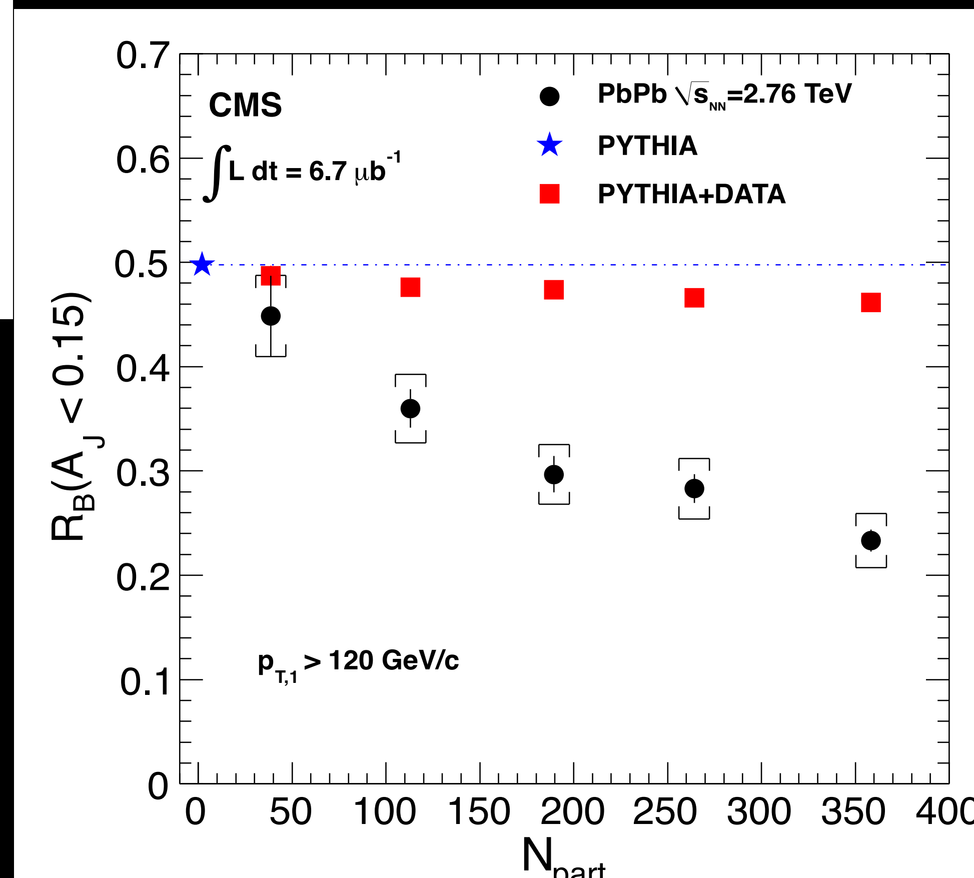
Di-Jet Asymmetries at the LHC – CMS

CMS, B. Wyslouch, C. Roland QM 2011



$$A_J = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$$

Corrected for underlying event flow

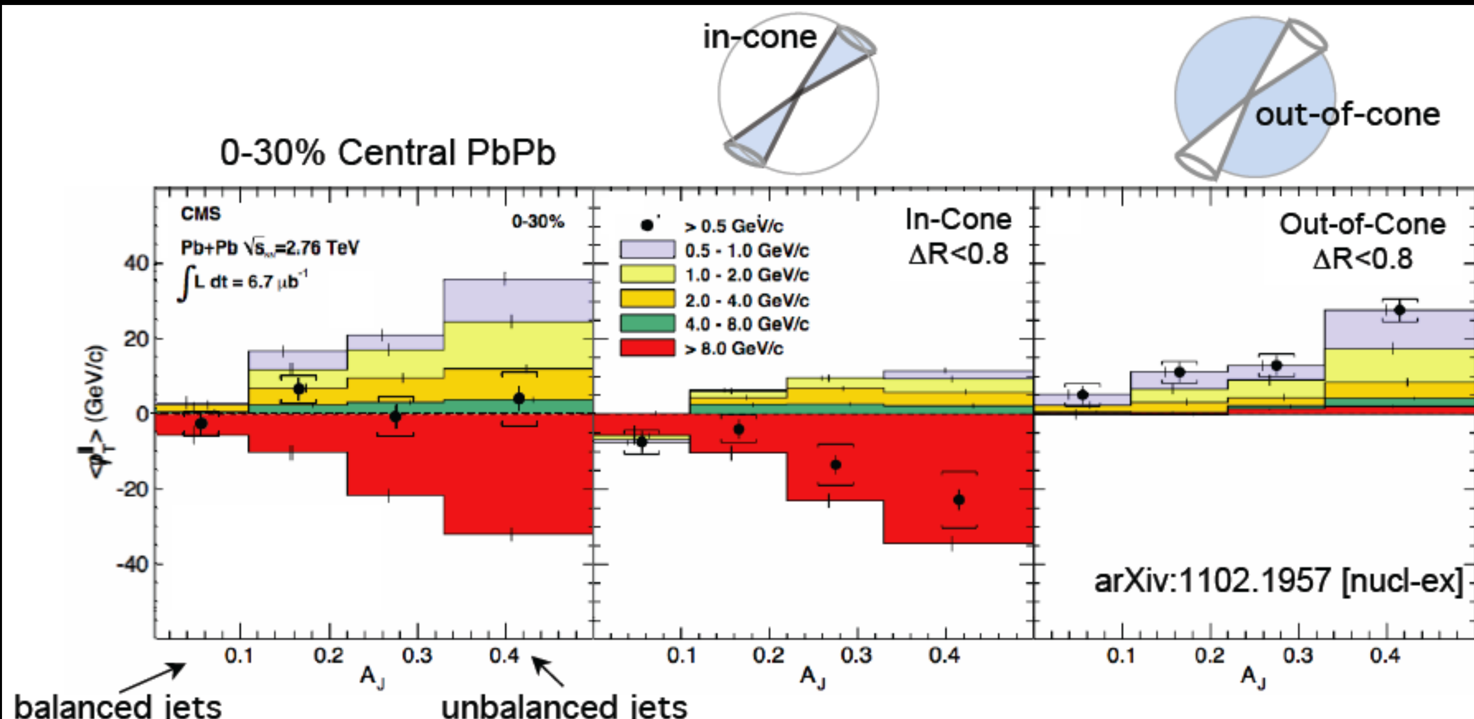


Di-jet momentum imbalance

Di-Jets at the LHC – CMS

CMS: arXiv:1102.1957

CMS, C. Roland QM 2011



Di-jet energy imbalance offset by lower momentum particles opposite leading jet and outside away-side jet.

Jet suppression factor ~ 2 in most central events

No observed jet E_T dependence of fragment j_T distn's

Slight softening of fragment z distn's

No significant broadening of j_T

Large di-jet asymmetries observed

No di-jet angular de-correlation observed

Di-jet energy (momentum) imbalance offset by low momentum particles opposite leading jet & outside away-side jet

Future Prospects for the LHC Heavy-ion Program

LHC Heavy Ion Program

- completed - "planned" - "planned shutdown"

2010 – $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb (4 weeks)

2011 – $\sqrt{s_{NN}}$ = 2.76 TeV p+p (completed), Pb + Pb (4 weeks), p + Pb tests

2012 – $\sqrt{s_{NN}}$ = 2.76 TeV Pb + Pb or p + Pb / Pb + p

2013 – Shutdown for maintenance, installation & repairs

2014 – +6 month shutdown - LINAC 4, vertex detector upgrades
$\sqrt{s_{NN}}$ = 5.5 TeV Pb + Pb for physics

2015 – $\sqrt{s_{NN}}$ = 5.5 TeV ***high L*** Pb + Pb to reach 1 nb^{-1}

2016 – $\sqrt{s_{NN}}$ = 5.5 TeV ***high L*** Pb + Pb or p + Pb / Pb + p hard probe physics

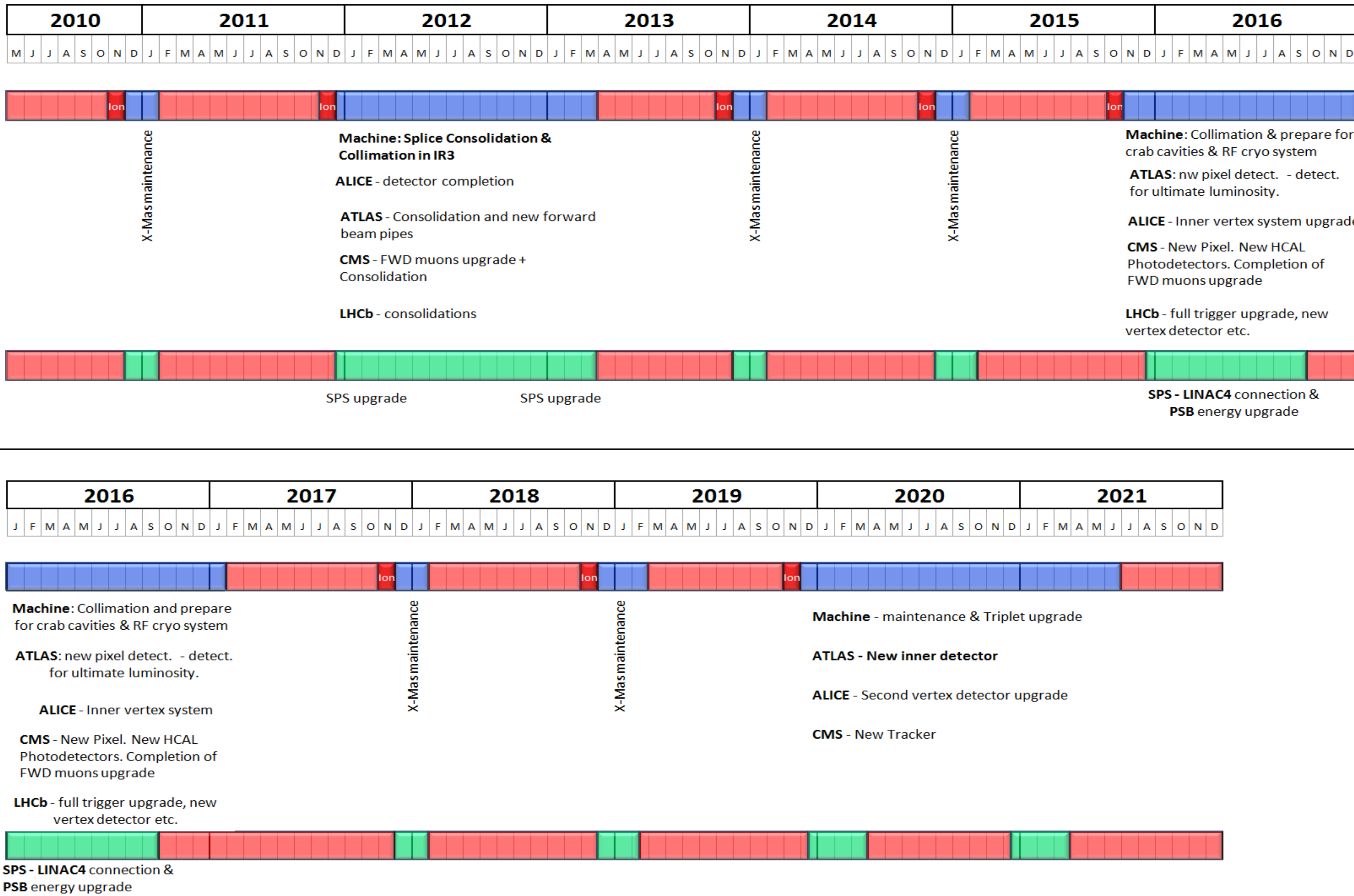
2017 – Major upgrade shutdown - IR Quads & detector upgrades

2018-19 – $\sqrt{s_{NN}}$ = ***high L*** 5.5 TeV p + Pb or d + Pb (if source & LINAC ready)
hard probe physics

2020 – Physics with ***very high L*** Ar + Ar (10^{29} $cm^{-2}s^{-1}$) hard probe physics

2021 – possible shutdown….upgrades

The LHC 10-Year Technical Plan (add 1 yr!)



Questions to Ponder: Require Detailed Work, Ingenuity – Quark-Gluon Plasma at RHIC & LHC

What are the properties & constituents (vs. T) of the QGP?

- quarkonia (screening vs LQCD)

Can we understand parton energy loss at a fundamental level? RHIC & LHC

- u&d,g,c,b differences should reveal medium properties!

How does hadronization occur? – the question never addressed!

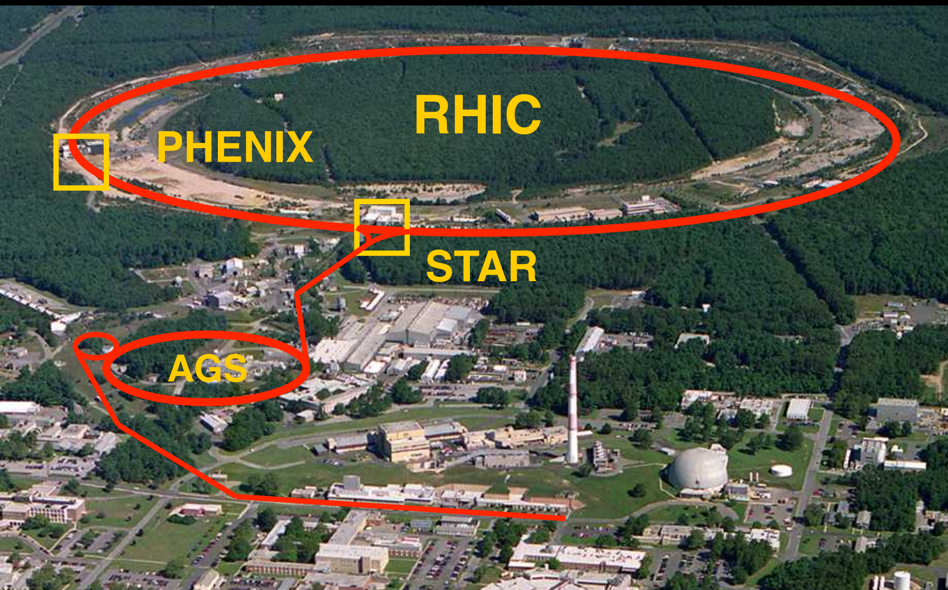
QCD Phase Diagram - featureless (above/near Tc)? Coupling strength vs T….

Are there new phenomena? – What about the Chiral magnetic effect? Others?

Ranges of validity of the theories (non-pQCD, pQCD, strings)?

- Can there be new developments in theory (lattice, hydro, parton E-loss, string theory…) and understanding……across fields……?

Heavy Ion Programs at RHIC and LHC



Cover 3 decades of energy
in center-of-mass

Opportunities to investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!